Quaternary erosion agents, Holocene landscapes and soils of the Tamar Estuary Basin, Tasmania

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Declaration

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Deborah L. Hunter

3rd July 2017

Annotation

This thesis is a corrected text following examination.

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Abstract

Ongoing siltation in the upper Tamar Estuary is problematic for reasons of amenity, navigation, human health and Launceston city's flooding hazard. Regional authorities commissioned catchment to estuary sediment flux computer-based modeling in 2008 to identify sediment sources or erosion hotspots. It had been over 20 years since sediment inputs were quantified and sedimentation processes in the Estuary identified.

The present research critically considered the modeling results in the context of the attribution of sediment provenance to land use and the validity of application of the Revised Universal Soil Loss Equation (RUSLE) using the KLS component of the equation from digital soil mapping. Two major research themes developed:

1. The role of land use in sediment flux to the Tamar Estuary compared to "natural" rates of change was placed in context by researching landscape change through recent earth history to Pleistocene human migration and contemporary history.
2. Soils from a pilot study area were sampled and characterised to assess the feasibility of using soil types from existing soil mapping as an alternate basis to land use in modeling and to improve field data quality and resolution for sediment flux modeling as well as contribute data to the Soils and Landscape Grid of Australia (SLGA).

The literature was reviewed for qualitative pre-historical analyses and presentation, while landscape spatial data analyses were undertaken using a project geographic information system (GIS), using both digitised historical maps and digital datasets.

The pilot study area selected for soil characterisation and detailed examination of modeled erosion hazard was the upper South Esk catchment in the north-east highlands

of the Tamar basin, over 1,000 km^2 in area. Modeling suggested the area had some of the highest exports of sediment in the basin, which is known for its apparently highly erodible granite-based soils.

Pre-historical and historical phases of landscape instability and erosion events were identified and documented, placing historical human settlement and land use in long term context. It was found that the arid glacial climates and Aboriginal land management practices of the Pleistocene provided an abundance of sediment available for aeolian transport across the Tamar catchments from Tasmania's centre and west, a sediment source to the Tamar and its Esk rivers catchments by "natural" or background processes now ceased. Since then, erosion rates reduced and stabilised and a virtual *dynamic equilibrium* regime of sedimentation and scour in the estuary was established, albeit within the more gradual evolution of a drowned river valley infilling with sediment.

Nevertheless, while according to the literature the total suspended sediment (TSS) values of the Esk rivers are very low compared to world rivers, the dominantly fine (<63 µm) sediment flux has increased post-colonisation. From the literature research and GIS, the resolution or detail of historical data was sufficient to indicate four periods of historic landscape instability, the last still extant. These periods of instability, in which landscapes have been more vulnerable to erosion and siltation of the Tamar Estuary likely increased, can be attributed to a combination of specific climatic ("natural") and anthropogenic (land use) factors. While the development of sustainable agricultural systems has been prioritised, research suggests that the reinstatement of a dynamic equilibrium that minimises estuarine siltation is uncertain in the context of anthropogenic climate change and landscape transformation.

Contemporary geological mapping was found on the basis of soil geochemistry to be reliable for use, within specified limitations, in sediment provenance modeling or sediment source attribution. The project GIS, compiled from geological spatial data, land systems and contemporary land use and vegetation, enabled the classification of soils by four geological parent materials using strategic sampling stratification. The cartography produced includes land use and soil type overlays on erosion hazard values.

Elemental properties of top- and sub-soil samples from 54 sites were analysed using inductively coupled plasma mass spectrometry (ICP-MS) following mixed acid (HNO_3-HF-HCl) digestion. Subsequent to elimination of redundant elemental properties out of 35 analysed, the four soil types were differentiated by discriminant (function) analysis (DA or DFA) using a "fingerprint" of 13 elements. A satisfactory proportion (87%) of the samples were robustly classified, including discrimination of the alluvium derived from three other soil types, one of which comprised 50% of the total pilot area.

The sampling and analytical methodologies developed represent a minimalist yet robust approach, optimised for a sole researcher and/or limited facilities, suitable for application in sediment flux modeling or direct suspended sediment fingerprinting techniques in physiographically complex catchments such as the Tamar basin. The soil work undertaken and methodologies developed have value in confirming soil characteristics in the study catchment and in application in ground truthing where and as required. It is intended by the Department of Primary Industry, Parks, Water and Environment (DPIPWE) to combine the project soil results with the new LIDAR (light detection and ranging) products when they become available, to enable more useful second generation soil mapping products e.g. for erosion hazard assessment at the sub-catchment scale.

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Numerous field assistants either shared delightful clear alpine days or braved the *La Niña* conditions that beset much of the fieldwork phase of the project. Thank you to Andrew Seen and Greg Unwin and UTas volunteers Brigid Morrison, Sophie Buttery, Chloe Hill, Deborah Collings, Laura McKew and Deb Lynch for turning up for false starts when the roads were flooded, for clearing fallen limbs, checking the depth of snow on the road and putting up with the leeches.

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For Marjorie Jean Hunter (1925-2012).

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Figure 1.2: Launceston’s seaport at high tide (2013).

1.1 Introduction to the siltation problem and its geographical context

The island state of Tasmania is 68,400 km^2 in size, including its offshore islands, and lies astride latitude 40^{o}S and longitude 43^{o}30’E. Launceston, the second largest city in Tasmania with an urban population of 67,179 in 2012 (Australian Bureau of Statistics, 2013), lies at the head of the Tamar estuary (known as the *Tamar River*) (Figure 1.3). Its suburbs extend over the surrounding floodplains and hillsides.

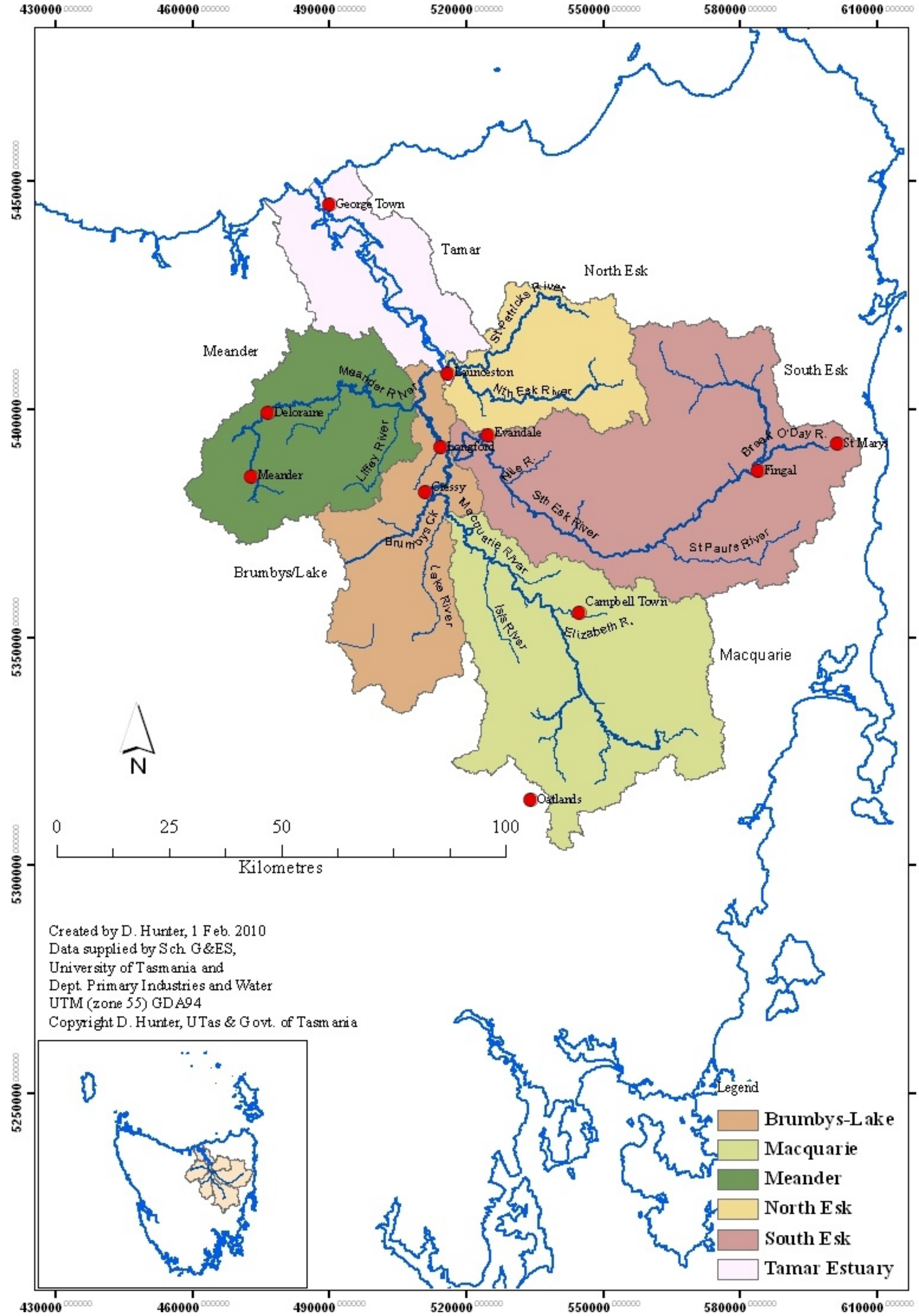


Figure 1.3: Tamar Estuary and Esk rivers basin, showing component catchments. Launceston is found at the confluence of the Esk rivers at the head of the estuary. The soil study area consists of the upper South Esk catchment, upwards from the confluence of the South Esk and Break O'Day Rivers. The northern Midlands plains occupy the region between the confluence of the South Esk and Macquarie Rivers and Oatlands.

At approximately 100 km^2 in area, the Tamar is one of Tasmania's largest estuaries, extending 70 km from its head at the confluence of the North and South Esk Rivers north to Bass Strait at Low Head (Gunawardana & Locatelli, 2008). While siltation of the upper estuary is progressive and has long been regarded as problematic, understanding of the Tamar estuary's fundamental hydrodynamics and siltation processes was poor until the 1980s (Foster *et al.*, 1986). This is because the Tamar is a mesotidal drowned river valley, a type of estuary uncommon in southeastern Australia and the only one of its kind in Tasmania (Sheehan, 2008). The Tamar estuary is a narrow, tidal watercourse. The typical morphology of the upper two thirds of the estuary consists of intertidal sediment banks and a channel conducting bidirectional flow (Pirzl & Coughanowr, 1997). In contrast, other estuaries of this region of Australia are dominantly shallow, ephemeral barrier estuaries (Sheehan, 2008).

Frequent dredging and raking (during high fresh flows) of the upper Tamar estuary is required to maintain the port shown in Figure 1.2. However, subsequent siltation is rapid, compromising both amenity and environmental quality. It is problematic for both commercial and recreational navigation (Figure 1.1), human health, and Launceston city's flooding hazard. The necessity of frequent and costly silt removal exacerbates community concerns over whether erosion in the catchments and estuarine siltation have increased over "natural" rates (Hydro Tasmania, 2003; Aquenal Pty Ltd & Department of Environment, 2008; Attard *et al.*, 2011).

In recent decades, studies have been undertaken into estuarine siltation processes followed by studies aimed at identifying the sources of suspended sediment input (Tamar Estuary and Esk Rivers Program, 2015). Estuarine sedimentation processes were reported by Foster *et al.* (1986). Substantial freshwater inputs at the head of the Tamar estuary deliver suspended sediment from a large 10,206 km^2 drainage basin. Dominantly clay and fine silt particles (<10 µm), the sediment remains in suspension without settling in Trevallyn Dam (on the South Esk River near its outlet to the estuary), passing over the spillway or through the power station into the estuary. Only then, flocculation of suspended sediment particles in the brackish water assists the settling out ("salting out") of sediment along the estuary (Foster *et al.*, 1986; Attard *et al.*, 2011). The South Esk River is shown entering the head of the Estuary in flood in Figure 1.4.

Figure 1.4: Aerial view of flood flow entering the head of the Tamar estuary from the South Esk River (a 9,141 km^2 combined catchment) via Cataract Gorge. Trevallyn Dam is situated just upstream of this gorge. Photography by Matt Sheehan, 2007.

The tidal hydrodynamics of the sinuous main channel of the estuary are such that sediment flocs flushed toward the mouth of the estuary in periods of high river flows are returned to the upper estuary on flood tides and are not flushed down again on the lower energy ebb tides (Foster *et al.*, 1986; BMT WBM Pty Ltd, 2008; Attard *et al.*, 2011). Lacking coarse fluvial sand, the intertidal beds of the upper two thirds of the estuary are composed mainly of fine mud that develops a scour resistant crust due to tidal wetting and drying cycles (Pirzl & Coughanowr, 1997).

The 1955 commissioning of the Trevallyn/Poatina hydroelectric Power Scheme saw partial amelioration of the problem (Foster *et al.,* 1986). There was an overall increase in fresh water inputs, a reduced incidence of low flows from the South Esk and better flushing of the upper estuary via the power station tailrace. However, siltation rates remained problematic and it was apparent they were still increasing. Indeed, it has been found that sediment input to the estuary has increased by as much as 250% over the history of Launceston's port (since before European settlement) (Tamar Estuary and Esk Rivers Program, 2015),

1.2 Previous siltation studies and the land use controversy

It was first observed by Foster *et al*. (1986) that while concentrations of suspended sediment in waters entering the head of the Tamar Estuary are generally low, the annual siltation rates are high due to a massive annual flow that drains from the 10,206 km^2 basin of the North and South Esk Rivers. Siltation rates were calculated by Foster *et al*. (1986) using linear regression analysis of sediment rating station data. It was not until

2008 that the first catchment to estuary sediment flux investigation was conducted in the Tamar basin, when the Natural Resource Management organisation of Northern Tasmania (NRM North) commissioned a computer-based model (Gunawardana & Locatelli, 2008). The *WaterCAST* model found that the South Esk basin (9,141 km^2), including the Meander, Macquarie, Brumbys-Lake and South Esk catchments, was responsible for 78% of the annual suspended sediment load entering the estuary (Tamar Estuary and Esk Rivers Program, 2015), the majority from upper catchments during flood flows (Figure 1.4), consistent with earlier findings (Foster *et al.*, 1986; Bobbi *et al.*, 1996; Gunawardana & Locatelli, 2008; BMT WBM Pty Ltd, 2010).

The *WaterCAST* model estimated both pre-development (pre- British colonisation) and contemporary suspended sediment yields in catchment divisions (BMT WBM Pty Ltd, 2010; Tamar Estuary and Esk Rivers Program, 2015). The annual average contemporary sediment input from the South and North Esk Rivers catchments to the Tamar estuary was estimated to have increased to 74,722 t from a pre-development annual average input of 31,500 t (BMT WBM Pty Ltd, 2010; Tamar Estuary and Esk Rivers Program, 2015). Contemporary erosion rates were estimated on the basis of land use, and the highest sediment yields were associated with high rainfall and land degradation.

The *WaterCAST* model drew upon existing physical and climatic data, collected from a limited number of long-term hydrological data collection points on the Esk rivers. The spatial distribution of these data points was more suited to the irrigation water management needs that they were established to serve, rather than to catchment modeling applications (BMT WBM Pty Ltd, 2010). Direct calibration of the model at sub-catchment scale was not possible as catchment outlets (river confluences) were too remote from access to allow for sampling, monitoring and direct measurements that may calibrate the model. Neither did the catchment *divisions* created for the purposes of modeling within catchments equate with sub-catchment boundaries, precluding direct calibration at greater resolution in the future (BMT WBM Pty Ltd, 2010).

Data specific the greater South Esk catchment that dominates suspended sediment inputs to the head of the Tamar Estuary was further considered. In the study that pre-dated the *WaterCAST* model (Foster *et al.*, 1986), the mean annual total suspended sediment (TSS) input at the estuary from the South Esk River alone for the period 1924-1979 was calculated at 39,300 t. *WaterCAST* modeling (BMT WBM Pty Ltd, 2010) estimated the contemporary average TSS at 43,543 t, with an annual range from 1980 to 2008 since Foster *et al.* (1986) at 39,440-54,400 t, from drought to flood years.

The *WaterCAST* attribution of annual TSS input to the Tamar estuary by land use has been controversial. It was found that forestry activities delivered 38% (for 24% of land area), agriculture 26% (48% of land area), green (nature conservation) areas 26% (24% of land area) and urban 10% (3% of land area) (BMT WBM Pty Ltd, 2010). Outside urban areas, it was found that agriculture land use was least responsible for erosion (both in absolute and areal terms) while forestry caused the most erosion.

The land use attribution appears reasonable. While agriculture land use dominates the catchments, most agriculture is in low rainfall regions at low altitudes. *WaterCAST* modeling associated the greater part of TSS generated in the Tamar basin with origins in the high rainfall upper catchments of the North and South Esk Rivers in Tasmania's northeast highlands and a minor component from the high rainfall upper Meander catchment in the west (BMT WBM Pty Ltd, 2010).

With physiographic settings (elevation) confounding land use signals in sediment flux modeling, the interpretation of *WaterCAST* forestry land use results in the BMT WBM Pty Ltd (2010) report was appropriately cautious. It was stated that while forestry sediment yield results were the highest for land area, both forestry and reserved conservation lands primarily occupy regions of high rainfall and increased slope gradients and that high sediment yields may reflect these factors and erodible soil types rather than land management practices. Notwithstanding these observations or caveats, the land use basis for sediment flux modeling was politically unpalatable.

Forestry industry proponents openly disputed the significance of sediment generation from forestry operations during the presentation seminar of the *WaterCAST* model findings held at Launceston in May 2009. Indeed, forestry has been dogged by controversy and public expressions of community division since the 1970s, associated with the rapid rise of industrial scale forestry in Tasmania (Kirkpatrick & Dickinson, 1982; Kirkpatrick, 1991; Beresford, 2015). The industry resisted rising criticism from other sectors of the community who saw the industry's expansion as being at the expense of "high conservation value" native forests and other "non-wood" values such as local water quality (Beresford, 2015).

Subsequent to the Launceston presentation, forestry practices and self-regulation were defended to stakeholders during a field trip of upper South Esk catchment forestry in August 2009 (Figure 1.5).

Figure 1.5: Typical example of intensive forestry operations in the upper South Esk catchment, photographed during the post *WaterCAST* model seminar field trip, August 2009.

A substantial area of this high rainfall region subject to extensive clearing for intensive forestry occupies soils derived from granite igneous rock, known by forestry practices scientists to be highly vulnerable to erosion (Grant *et al.*, 1995; Laffan *et al.*, 1998; Laffan *et al.*, 2003; Forest Practices Board, 2005) (Figure 1.6). Indeed, in a study in northwestern Australia, Wasson *et al.* (2002) found 96% of sediment in the Lake Argyle reservoir came from highly erodible soils of a geological unit occupying <10% of the catchment, 80% from gully and channel (subsoil) erosion.

Figure 1.6: Sheetwash erosion followed forestry operations on granite-derived soils, upper South Esk catchment (2011). The pale regolith is visible, denuded of groundcover and soil.

Agricultural land erosion control has been recognised as requiring improvement. Loss of riparian vegetation, grazing stock access and modification of watercourses, including changes to stream bank geomorphology and removal of physical impediments to sediment entrainment during agricultural development, are known to increase suspended sediment loads downstream (Fryirs *et al.*, 2007). The *WaterCAST* modeling (BMT WBM Pty Ltd, 2010; Tamar Estuary and Esk Rivers Program, 2015) specifically found that current flows in rivers of the Tamar basin have increased by about 50% since colonisation due to reduced filtering and buffering in the system and non-quantified inter-catchment transfers (i.e. Poatina/Trevallyn hydroelectric scheme).

(Tamar Estuary and Esk Rivers Program, 2015). The TEER *Water Quality Improvement Plan* (WQIP) predicted the current rate of estuarine siltation would continue unless authorities and the community engage jointly to improve protection of soils in the catchments (Tamar Estuary and Esk Rivers Program, 2015).

1.3 Contemporary erosion mitigation measures

Increased streambank erosion in agricultural areas of the Esk Rivers catchments (Bobbi *et al.*, 1996) began to be addressed in recent decades by individual landholders and community-based groups conducting remedial works on major streams (for example Breshnehan, 1995; Figure 1.7).

Figure 1.7: River bank remedial engineering with spaced rock barriers, South Esk River, 12 km north of Fingal (2010). Exotic forestry plantations cloak the alluvial plain and hills in the middle distance.

NRM North has been actively engaging with agricultural landowners on a regional basis with a view to reducing erosion in headwaters (smaller hydrological components of the catchments) by progressive adoption of stock exclusion measures, better stream protection practices and rehabilitation (Figure 1.8).

Figure 1.8: Gully erosion in an unprotected headwater stream on agricultural land in the upper Fingal Valley, eastern South Esk catchment, 2009. Photograph: NRM North.

Rapid development in irrigated agriculture has increased the urgency in addressing lowland erosion in recent years, for example stream rehabilitation to buffer against soil entering streams (Gunawardana & Locatelli, 2008). The *WQIP* developed a systematic agricultural erosion mitigation approach, guiding prioritisation and decision making in groundcover improvements, reduction of livestock access to streams and revegetation of riparian zones (Tamar Estuary and Esk Rivers Program, 2015). The *WQIP* projections were sensitive to stakeholder input, land use controversies and the expense of mitigation measures. With a strong focus on mitigation of agricultural land erosion, the likely best improvement envisaged was a forecast 6% reduction in sediment input to the estuary (Tamar Estuary and Esk Rivers Program, 2015).

The *Forest Practices Code* (FPC) was introduced in the mid 2000s to mitigate the environmental impacts of forestry through industry self-regulation (Forest Practices Board, 2005). It was noted in the WQIP (Tamar Estuary and Esk Rivers Program, 2015) that sediment production from new forestry operations (coupes) following the introduction of the FPC has fallen by as much as 8%, however industrial broadacre forestry was well-established prior by the time of the Code's introduction. Pre-FPC practices have not been altered, but have continued on pre-FPC coupes into subsequent crop rotations (for example, Figure 1.5, p 10). The *WQIP* recommended pre-FPC forestry coupes be identified and streamside reserves established where possible before (further) harvest.

It may be concluded that agriculture has received the most attention in catchment management of the present decade partly because 1. the forestry industry is self-regulating, 2. agriculture land use covers the greatest land area, 3. agricultural practices have been increasing in intensity (i.e. irrigation) and 4. it appears difficult to justify increasing scrutiny and erosion control measures on forestry lands when the high altitude climatic signal confounds the land use signal. Clearly, improvements in catchment data could increase confidence in the modeling and potentially lead to better decision-making in catchment management recommendations. Notwithstanding the socio-political context, if knowledge of erosion processes and research methods were improved, greater community co-operation, more effective targeting of erosion control measures may be possible and better outcomes may be achieved.

1.4 Consideration of validation of suspended sediment modeling in the Tamar Basin and further research

While infilling of the Tamar estuary is certainly an inevitable "natural" evolution (Foster *et al*., 1986), the environmental sustainability of industrialised land use in the catchments calls for a comprehensive assessment of factors potentially exacerbating siltation. In consideration of what research would make a significant contribution to existing knowledge, the right questions must first be asked. They include:

- Is the *WaterCAST* finding reasonable that siltation of the Tamar is now occurring at a greater rate than pre-European background or "natural" rates,
- Is the modeling of contemporary TSS values on the basis of post-colonial land use justified, especially without calibration by direct measurement at sub-catchment outlets,
- Have all relevant factors been taken into account in modeling,

- What alternative methods could be used to calibrate the *WaterCAST* model,
- In the absence of sub-catchment calibration of the sediment modeling, what evidence could be found by literature research to explore the *WaterCAST* findings, and
- Further, what is the likely influence of climate change over recent earth history and pre-European indigenous Tasmanians on erosion processes, relative to post-colonial land use?

In summary, decisions on erosion mitigation measures in the Tamar Basin have been formulated and are being implemented from the results of sediment flux modeling based on limited hard baseline data (BMT WBM Pty Ltd, 2010; Tamar Estuary and Esk Rivers Program, 2015). The model was based on hydrological data collected for unrelated purposes and has not been validated or calibrated by alternative techniques. The importance of testing model assumptions has been shown elsewhere in Australia (Caitcheon *et al.*, 2012).

Further, land use in the Tamar Basin was constantly evolving and the use of a more fundamental basis to suspended sediment flux modeling may assist understanding the effects of land use. In researching more practical and direct approaches for discerning sediment sources than in the *WaterCAST* land use modeling, a geological (soils) basis was considered.

Chemical "fingerprinting" of suspended sediments and "unmixing" of TSS by origin on the basis of geology is a well-established approach (Walling, 2005; Davis & Fox, 2009; Collins *et al.*, 2010). Typically, the chemical (and often physical) properties of soils of the catchment are characterised and their contribution distinguished statistically in the

TSS sampled from catchment outlet(s). However, consideration of the use of these techniques to directly attribute the provenance suspended sediment was precluded by the remoteness of potential sampling sites from access. Therefore, research into other contemporary techniques was undertaken.

The relationship of modeled sediment flux rates and land use to geology is difficult to examine using existing data. The *erosion risk* input data used in *WaterCAST* modeling fell short of a comprehensive calculation of the (revised) universal soil loss equation (RUSLE) (see CSIRO, 2016). While soil carbon, topsoil permeability and structure (*KLS* factors) were known, the number and distribution of discrete erosion sites were unknown and the resolution of component environmental data used was limiting. Improvements in erosion hazard assessment used in the modeling are imminent (Kidd *et al.*, 2015), and it appeared there could be value in working to improve and expand the data in this field on the Soils and Landscape Grid of Australia (SLGA).

Ground truthing for upcoming improvements in remote sensing incorporating LIDAR elevation models and multi-spectral satellite imagery and derivatives (Kidd *et al.*, 2015) holds much promise for improving future modeling, compared to more traditional “indirect” approaches to erosion monitoring and sediment flux prediction or chemical fingerprinting. There are two fundamental contemporary approaches in determination of the sources of suspended sediment in river systems and the respective contributions of each source to the total sediment load:

1. *Indirect assessment* by extrapolation is traditionally undertaken by identifying and measuring erosion at its sources, for example Selby (1993), or by modeling (BMT WBM Pty Ltd, 2010) and

2. *Direct measurement* of the suspended sediment load (or the "sink") below the catchment outlet and apportioning the provenance of the sediment to its sources using techniques such as sediment biogeochemical "fingerprinting" (for example, after Collins *et al*., 1998; Davis & Fox, 2009; Collins & Walling, 2004; Walling, 2005) magnetic fingerprinting (Hatfield & Maher, 2008) or ^{137}Cs fingerprinting (Caitcheon *et al.*, 2012). Representations of sediment sinks have included sampling suspended sediment (for example, Viers *et al.*, 2008), floodplains or river sediment cores (Oliver *et al.*, 1999; Hughes *et al.*, 2009) or lagoon/estuarine/coastal sediments (Douglas *et al.*, 2009; Douglas *et al.*, 2010). Further groups of possible sediment tracer properties for direct measurements are discussed elsewhere for example, in Davis and Fox (2009).

Indirect assessment involves measuring erosion in the catchments and applying the Universal Soil Loss Equation (USLE), where the USLE is expressed as A= RKLSCP, where: A= the soil loss, R= the rainfall erosivity factor, K= the soil erodibility factor, L= the slope length factor, S= the slope gradient factor, C= the cropping management factor, P= the erosion control practice factor (Selby, 1993). Identifying the sources of suspended sediment flux in large drainage basins like that of the Tamar using traditional indirect sediment estimations from erosion monitoring techniques such as erosion pins and troughs and/or measuring suspended sediment inputs from sub-catchments by long term monitoring, usually presents substantial spatial and temporal sampling constraints (Collins *et al.*, 1998). It has been shown elsewhere that in addition to data collection problems, different USLE calculation methods give rise to different values between studies using such techniques (Selby, 1993).

The *WaterCAST* modeling (BMT WBM Pty Ltd, 2010) represents a variation of the indirect technique. In this case, the link between source and sink was established by assigning a TSS value to each land use and then calculating a predicted suspended sediment load from TSS, rainfall and land use area. The predictions were calibrated against measured flow and TSS data from a limited number of pre-existing monitoring locations across the Tamar basin. According to Zhang *et al*. (2012) while samples from pre-existing ("routine") water monitoring stations in large drainage basins can be used for sediment provenance information, it should be regarded as preliminary only.

Direct methods relying on sediment sampling were faced with similar prohibitive constraints as the *WaterCAST* modeling. Catchment outlets for floodwater (suspended sediment) sampling in the Tamar basin are remote from road access and difficult to access. The alternative to *suspended* sediment sampling, the sampling of siltation, could not be conducted on the Esk Rivers' floodplains or in the Trevallyn Dam on the South Esk just before it drains into the estuary, due to sediment being transported in suspension until it flocculates and "salts out" in the estuary (Foster *et al.*, 1986; BMT WBM, 2008). Estuarine sediment (grab or core) sampling to represent the sediment sink/target would be inappropriate due to the dredging history, estuarine hydrodynamics (cyclic scour and tidal redistribution) and inclusion of sediment from the Tamar estuary's immediate urban catchment (Foster *et al.*, 1986). It was considered these factors implied substantial uncertainties in any application of chemical fingerprinting techniques in the Tamar basin. The likely fingerprinting uncertainties from sediment sink sampling intending to estimate changes in erosion with land use over time or in the present were considered unacceptable.

Instead, it was considered that improvements in erosion hazard data in the catchments could increase the predictive power and reliability of *WaterCAST* modeling. Remote sensing is new generation technology that is coming of age, and is practical given the Tamar basin's areal scale (>10,000 km^2), the complexity of the topography and geology and its remoteness. Ground truthing, i.e. field-verification of available geological data, could assist in verification of remote sensing and contribute towards improved erosion hazard modeling. An investigation of a practical geochemical classification of soil types could be designed from chemical fingerprinting techniques and tested for robustness in reducing complexity of geological data.

Improved soils data in the catchments may influence a rerun of the *WaterCAST* model using geology as an alternative primary geographical unit to land use. It may be argued that community engagement could be optimised if the land use controversy could be reduced. Sediment source attribution would possibly be more politically palatable. If the high sediment yield from forestry, as modeled by *WaterCAST,* were confirmed by an alternative primary approach, a review of forestry practices aimed at reducing erosion may gain increased community support.

Therefore, sampling and chemical analysis of the soils of a "pilot study area" towards confirming geological mapping was seen to offer valuable potential in the improvement of catchment data. Field techniques useful for ground truthing could be trialed and geochemical analyses could be conducted using inductively coupled plasma mass spectrometry (ICP-MS). The upper South Esk catchment including the Break O'Day catchment (1,016 km^2) was chosen as the most appropriate pilot area since, of the component river systems, the South Esk River carried by far the greatest annual flow

(2,145,837 ML) and suspended sediment load (0.045 Mt) while forestry land use, implicated by modeling to have high sediment yield, dominates the higher altitudes of the sub-catchments (BMT WBM Pty Ltd, 2010; Tamar Estuary and Esk Rivers Program, 2015). If time allowed, suspended sediment could be sampled at the (sub-) catchment outlet, being one of the few in the greater South Esk catchment with road access. The pilot study catchment has a complex expression of surface geology, including acid and basic igneous rock, sedimentary rocks and Quaternary sediments (Figure 1.9), with varied topography substantially influenced by Quaternary climatic processes (Figure 1.10).

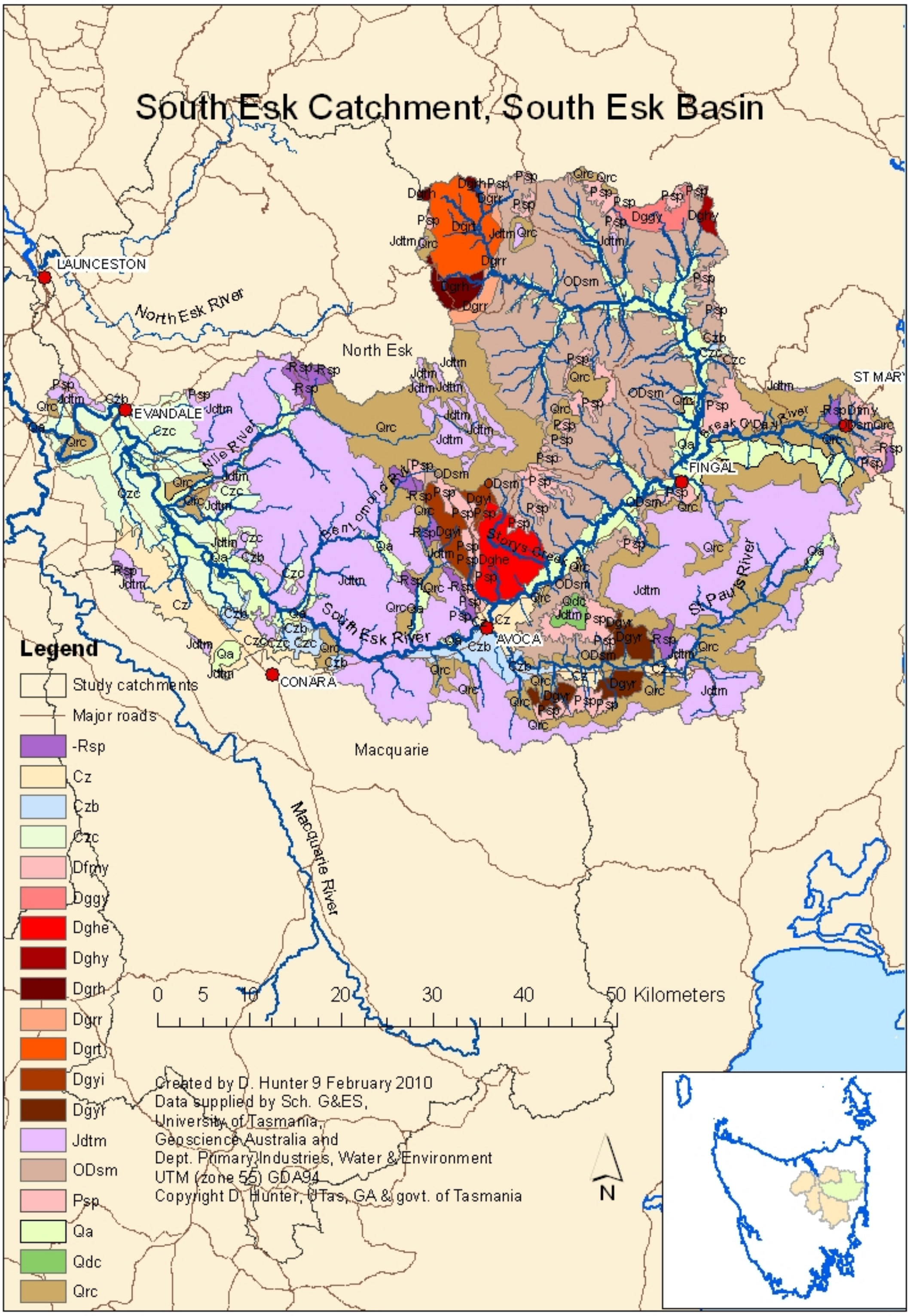


Figure 1.9: South Esk catchment, showing surface geology. The upper catchment pilot study area extends east and north from Fingal, shown near the major river confluence.

Figure 1.10: Soil pilot study catchment looking east towards St Marys from a dolerite outcrop 14 km northwest of Fingal. Farming land occupies the broad alluvial valleys, with exotic plantations and native forests on the midslopes and subalpine native mixed forest in the foreground. The Break O'Day River valley extends to the east from Fingal on the right and the upper South Esk River valley extends north to south (L-R) in the middle distance.

The pilot soil study area lies to the north and east of Fingal (Figures 1.3, 1.9 & 1.10). Landscapes vary from broad alluvial valleys with predominantly agricultural land use to deeply incised river valleys with land use mosaics of farming, forestry and native vegetation and rugged mountain tops with native alpine vegetation (Figure 1.10).

The pilot study area's physiography and surface geology are covered in detail in Chapter 4.

1.5 Aims and objectives and summary of the thesis

To answer the questions (pp 15-16), the aim was to facilitate better community and stakeholder engagement, decision making and outcomes in erosion management in the Tamar Basin catchments, towards more effective erosion control, reducing the rate of siltation in the Tamar Estuary. Essential to this is the context of whether the *WaterCAST* findings on TSS related to land use were reasonable.

The first objective (Chapter 2) was to synthesise a background on landscape evolution and stability over recent geological time, to qualitatively relate erosion and erosion processes in the present to the past. The synthesis was enhanced by quantitative GIS analysis of available spatial data on more recent landscape change (Chapter 4). This combined research represents a major synthesis of the environmental history and contemporary erosion pressures in the catchment.

The second objective was to assess the accuracy of available geological data in a substantial sub-catchment area of the Esk Rivers basin to determine whether the available mapping and project soil classification system accurately predicted distinctive soil types (Chapter 5).

The third objective was to test the hypothesis that soils of a pilot study catchment could be distinguished using geochemical characterisation on the basis of simplified soil types (Chapter 5). In realising the second and third objectives, this work would make a substantial contribution to soil information capture in Tasmania and the SLGA soils database.

The fourth objective was to examine the apparent relationships between erosion hazard mapping and geological and land use units upon which erosion mitigation efforts are currently based (Chapter 5).

This thesis presents the principle literature review in Chapter 2, which first examines Tasmania's landscape evolution and climate over recent earth history and the impact of the first human migration. The review then focuses in on the late Holocene and north-east Tasmania, addressing questions of community concern on "natural" (pre-historic) sedimentation rates and the effects of changing land use and climate.

Research methods and materials are found in Chapter 3, including quantitative desktop methods in landscape spatial analysis and experimental design as well as field and laboratory techniques.

In Chapter 4, the physiography of the Esk Rivers basin including the pilot study area is described. Quantitative analyses of pre-European landscapes, European immigration and landscape change to present are given, including discussion of the relative influence of anthropogenic and edaphic factors on siltation of the Tamar from the project geographic information system (GIS).

Field, laboratory and statistical results from the upper South Esk pilot study area are presented in Chapter 5, including field data verification and soils characterisation results. Non-parametric statistical techniques are used to confirm the geochemical classification of a spectrum of soils into main soil (parent rock) types. A discriminatory soil type characterisation is identified, systematic factors in sample reclassification are analysed, and erosion hazard analysis is examined in context of erosion-prone soil types, the present study and future modeling.

Chapter 6 evaluates the research results as a substantive synthesis of erosion processes in a catchment, a useful contribution to SLGA and as a trial of laboratory and fieldwork methods designed to assist erosion control in sustainable catchment management. The Chapter considers opportunities for further research.

1.6 References

Aquenal Pty Ltd and Department of Environment, P, Heritage and the Arts, (2008). State of the Tamar Estuary. Hobart.

Attard, M, Thompson, M, Kelly, R and Locatelli, A (2011). Tamar Estuary and Esk Rivers Ecosystem Health Assessment Program: Monitoring Report 2011. Launceston.

Australian Bureau of Statistics. (2013). "3218.0 Regional Population Growth, Australia." 2013, from http://www.abs.gov.au/AUSSTATS/.

Beresford, Q (2015). The Rise and Fall of Gunns Ltd. Sydney, University of New South Wales.

BMT WBM Pty Ltd (2008). Review of Foster (1986) Report on Sedimentation Processes. Brisbane, BMT Group.

BMT WBM Pty Ltd (2010). Tamar Estuary and Esk Rivers Catchment WaterCAST Model: Final Report. Brisbane, BMT Group.

Bobbi, C, Fuller, D and Oldmeadow, D (1996). South Esk Basin State of Rivers Report. Hobart, Resource Assessment Branch, Department of Primary Industry and Fisheries.

Breshnehan, S (1995). The Brumbys Creek rehabilitation program. The 4th Australian Stream Management Conference, 1994, Launceston**:** 114-119.

Caitcheon, GG, Olley, JM, Pantus, F, Hancock, G and Leslie, C (2012). "The dominant erosion processes supplying fine sediment to three major rivers in tropical Australia, the Daly (NT), Mitchell (Qld) and Flinders (Qld) Rivers." Geomorphology **151-152**: 188-195.

Collins, AL and Walling, DE (2004). "Documenting catchment suspended sediment sources: problems, approaches and prospects." Progress in Physical Geography **28**(2): 159-196.

Collins, AL, Walling, DE and Leeks, GJL (1998). "Use of composite fingerprints to determine the provenance of the contemporary suspended sediment load transported by rivers." Earth Surface Processes and Landforms **23**: 31-52.

Collins, AL, Walling, DE, Webb, L and King, P (2010). "Apportioning catchment scale sediment sources using a modified composite fingerprinting technique incorporating property weightings and prior information." Geoderma **155**: 249-261.

CSIRO. (2016). "Soil and Landscape Grid of Australia."

Davis, CM and Fox, JF (2009). "Sediment fingerprinting: Review of the Method and Future Improvements for Allocating Nonpoint Source Pollution." Journal of Environmental Engineering **135**(7): 490-504.

Douglas, G, Caitcheon, GG and Palmer, M (2009). "Sediment source identification and residence times in the Maroochy River estuary, southeast Queensland, Australia." Environmental Geology **57**: 629-639.

Douglas, GB, Kuhnen, M, Radke, LC, Hancock, G, Brooke, B, Palmer, MJ, Pietsch, T, Ford, PW, Trefry, MG and Packett, R (2010). "Delineation of sediment sources to a coastal wetland in the Great Barrier Reef catchment: influence of climate variability and land clearing since European arrival." Environmental Chemistry **7**: 190-206.

Forest Practices Board (2005). Forest Practices Code. Hobart, Forest Practices Board.

Foster, DN, Nittim, R and Walker, J (1986). Tamar River Siltation Study. Manly Vale, New South Wales, The University of New South Wales Water Research Laboratory.

Fryirs, KA, Brierley, GJ, Preston, NJ and Kasai, M (2007). "Buffers, barriers and blankets: The (dis)connectivity of catchment-scale sediment cascades." Catena **70**: 49-67.

Grant, JC, (Australia), NLP and Tasmania, FaFICo (1995). Forest soils of Tasmania : a handbook for identification and management Hobart, Forestry Tasmania.

Gunawardana, D and Locatelli, A (2008). Tamar Estuary Management Plan. Launceston, SFM Environmental Solutions Pty Ltd.

Hatfield, RG and Maher, BA (2008). "Suspended sediment characterization and tracing using a magnetic fingerprinting technique: Bassenthwaite Lake, Cumbria, UK." The Holocene **18**(1): 105-115.

Hughes, AO, Olley, JO, Croke, JC and McKergow, LA (2009). "Sediment source changes over the last 250 years in a dry-tropical catchment, central Queensland, Australia." Geomorphology **104**: 262-275.

Hydro Tasmania (2003). South Esk - Great Lake Water Management Review: Scientific Report on Tamar Siltation.

Kidd, D, Webb, M, Malone, B, Minasny, B and McBratney, A (2015). "**Eighty-metre resolution 3D soil-attribute maps for Tasmania, Australia**." Soil Research **53**: 932-955.

Kirkpatrick, JB (1991). "The Magnitude and Significance of Land Clearance in Tasmania in the 1980s." Tasforests: 11-14.

Kirkpatrick, JB and Dickinson, KJM (1982). "Recent Destruction of Natural Vegetation in Tasmania." Search **13**(7-8): 860-861.

Laffan, MD, Grant, HC and Hill, RB (1998). "Some properties of soils on sandstone, granite and dolerite in relation to dry and wet eucalypt forest types in Northern Tasmania." Tasforests **10**: 49-58.

Laffan, MD, McIntosh, P and Neilson, WA (2003). "Forest soils derived from granite in northern Tasmania: an overview of properties, distribution and management requirements." Tasforests **14**: 1-14.

Oliver, RL, Hart, BT, Olley, J, Grace, M, Rees, C and Caitcheon, G (1999). The Darling River: Algal Growth and the Cycling and Sources of Nutrients. Murray-Darling Basin Commission Project M386, CRC for Freshwater Ecology; CSIRO Land and Water.

Pirzl, H and Coughanowr, C (1997). State of the Tamar Estuary: A review of environmental quality data to 1997. Supervising Scientist Report 128. Canberra, Environment Australia, Commonwealth Department of Environment, Sport and Territories.

Selby, MJ (1993). Hillslope Materials and Processes. New York, Oxford University Press.

Tamar Estuary and Esk Rivers Program (2015). Tamar Estuary and Esk Rivers Catchments Water Quality Improvement Plan. T. NRM North. Launceston, NRM North.

Viers, J, Roddaz, M, Filizola, N, Guyot, J-L, Sondag, F, Brunet, P, Zouiten, C, Boucayrand, C, Martin, F and Boaventura, GR (2008). "Seasonal and provenance controls on Nd-Sr isotopic compositions of Amazon rivers suspended sediments and implications for Nd and Sr fluxes exported." Earth and Planetary Science Letters **274**: 511-523.

Walling, DE (2005). "Tracing suspended sediment sources in catchments and river systems." Science of the Total Environment **344**: 159-184.

Wasson, R, Caitcheon, G, Murray, A, McCulloch, MT and Quade, J (2002). "Sourcing Sediment Using Multiple Tracers in the Catchment of Lake Argyle, Northwestern Australia." Environmental Management **29**(5): 634-646.

Zhang, Y, Collins, A and Horowitz, A (2012). "A preliminary assessment of the spatial sources of contemporary suspended sediment in the Ohio River basin, United States, using water quality data from the NASQAN programme in a source tracing procedure." Hydrological Processes **26**: 326-334.

Chapter 2

Literature review

Figure 2.1: Erosion of Quaternary glaciofluvial sediments, Claytons Creek, South Esk catchment, pilot study area.

2.1 Agents of erosion in the Esk Rivers basin

Foster *et al.* (1986) noted high concentrations of fine (<10 µm) suspended sediments in the Esk Rivers, and could not state whether sedimentation had historically increased beyond that of the estuary "trying to return to its pre-dredging condition." While recent *WaterCAST* modeling (BMT WBM Pty Ltd, 2010; Tamar Estuary and Esk Rivers Program, 2015) found the Esk Rivers sediment flux had increased by about 250% compared to pre-development rates, cause attribution was problematic since the land use signal was confounded by other signals, especially climate.

While erosion is a natural process driven by gravity, the main environmental predispositions or variables influencing erosion are climate and geology, with the character of the soils and vegetation cover both dependent on and interacting with those influences in a complex manner (Selby, 1993). The magnitude of erosion is influenced by destabilising factors including tectonic uplift, climate change, fire frequency and human land use changes (Selby, 1993; Hesse & McTainsh, 2003; Colhoun *et al.*, 2010; Syvitski & Kettner, 2011). Fine fluvial suspended sediments, as found in rivers elsewhere in Australia (Oliver *et al.*, 1999), are a legacy of a long history of high climatic variability and aridity. However, in the continental setting, there is substantial contemporary aeolian sediment movement (erosion of dust by wind) from the arid interior to the river catchments, with dust supply in turn renewed to the interior by internally draining fluvial systems (Hesse & McTainsh, 2003). On the other hand, some world fluvial systems are still carrying elevated sediment loads in delayed response to Pleistocene conditions (Syvitski and Kettner, 2011). Sedimentation and erosion processes in the Esk Rivers basin have likely been consistent with those described by

Sigleo and Colhoun (1982), where the landscape has been subject to aeolian sedimentation due to glacial period aridity in concert with anthropogenic influences.

Sequential erosion events in Tasmania's highlands over the greater part of the last 100,000 years can be confidently related to glacial and periglacial processes (2.2.1). During the late Quaternary period, which is of particular interest to the present study, extended periods of low humidity and cold temperatures resulted in thinning of vegetation cover and aeolian erosion (Sigleo & Colhoun, 1982). Other agents of erosion included fires lit by Aborigines (2.2.2) and a modern period of a series of profound landscape changes, including an overall reduction in native vegetation cover since European settlement (2.3) (Ellis, 1985; Breen, 2001; Gilfedder *et al.*, 2003).

2.2 Prehistory of Tasmanian landscapes and the Esk Rivers basin

2.2.1 Earth history

The landforms of the Esk Rivers basin were being shaped prior to the Carboniferous period, more than 360 Ma (million years ago). The ancient Ordovician to Devonian Mathinna sediment beds of the northeast were laid down and intruded by granite (Jackson, 2005). Upthrusts to the east and west of the northern Midlands during the Jurassic and Cretaceous periods (from 200 Ma) formed the horsts and uplands of the study basin catchments, each side of the northern Midlands graben (a depression between faults). The upthrusts were accompanied by dolerite intrusions into the highland Permian-Triassic sediments. As Gondwana fragmented through the Tertiary period, Tasmania drifted northwards through about 13° of latitude, from 55°S to its present position at about 40°S, climates changing with changes in latitude, proximity to other land masses and the advent of a deep circumpolar current in the mid-Tertiary (Hill, 1990). During this period, the graben began to fill with silt. Two large lakes formed, fused into one and then sediment eroded from the uplands filled the graben to 800 m depth. River courses were changed by basalt extrusions that peaked at 22 Ma.

Climatic change, particularly over the last 30 Ma (latter Cenozoic era), dramatically affected both landscape and vegetation. Following the earlier Tertiary changes, conditions became more arid in Tasmania by the late Miocene (by 5 Ma) (Hill, 1990). Glacial-interglacial oscillations increased in amplitude over Pliocene-Pleistocene times, from 5 Ma into the Quaternary period (Jackson, 2005). Greater temperature fluctuations, widespread frost as well as reduced and more seasonal rainfall with summer droughts contributed to a reduction in rainforest species in Tasmania. A change in the seasonal climatic pattern in the late Pliocene (~ 3 Ma) from a summer precipitation to a winter precipitation caused massive changes in vegetation community structures (geographic expansion then contraction of rainforest and sclerophyll communities), species extinctions and a bioclimatically influenced predisposition to burning (Hill, 1990; Jackson, 2005). In the Australian region, the late Quaternary glacial-interglacial oscillations were expressed primarily in moisture availability variation (Kershaw *et al.*, 2003). Jurassic dolerite intrusions of sills and dykes in the uplands were progressively denuded of the overlying sediments with the result that aeolian (wind-blown) sands and alluvium accumulated in the valleys and atop the Tertiary sediments in the northern Midlands graben.

It is well established that the principal legacy of Tasmania's glacial history is a plentiful supply of physically weathered material available for mobilisation by erosion agents. In addition to the mass movement of material by glaciers and periglacial geomorphic processes such as solifluction, such destabilising climatic conditions increase physical weathering rates of exposed rock by mechanisms including ice wedging and thermal stress (Selby, 1993). During the Pliocene-Pleistocene glaciations prior to the Last Glacial period, cool desert conditions prevailed in the Midlands and dry alpine conditions prevailed on the Oatlands plateau in the south of the Esk Rivers basin (Hill, 1990). The landscape changing processes prevailing in these areas during the glacials have been described as "intense" (Jackson, 2005). Periglacial activity of the Last Glacial peaked around 23-16,000 years ago and the minimum effective precipitation period occurred 14-12,000 years ago (Williams *et al.*, 2009). Till (ground up rock fragments of all sizes) that had been deposited marginal to an ice cap near the Liffey-Poatina area in the west of the study basin became a source of wind-blown sand during these cold, dry and windy times (Kirkpatrick, in Gilfedder *et al*., 2003). The Midlands' aeolian deposits including lunette dunes originated during Pleistocene (Quaternary) glacial times, as did as fluvial origin sand sheets and saltpans.

2.2.2 The first Tasmanians

Pollen evidence and charcoal from the Darwin Crater, western Tasmania, suggests greater vegetation response over the last two glacial to interglacial transitions than the previous three cycles, with more open vegetation structures. This response and climatic setting coincides with the time frame for the arrival Aborigines in Tasmania according to most contemporary evidence (for example Jackson, 2005; Turney *et al*., 2008).

In Tasmania's first phase of human dispersion, "fire-stick farming" Aborigines first arrived from the Australian mainland by crossing a land bridge or small stretches of water in boats during glacial conditions some time between 70,000 and 35,000 years ago (Jackson, 1999; Kirkpatrick & Bridle, 2007). The dispersal of Aborigines to Tasmania has frequently been linked in the literature to profound landscape change, although the true significance of the contribution of Aboriginal use of fire in landscape transformation in Tasmania has been much debated (Thomas, 1993; Jackson, 1999; McIntosh *et al.*, 2009). Certainly, their numerous fires were obvious to the British colonists (for example MacKnight, 1998). Knowledge gaps remain regarding Aboriginal influence during the Holocene on landscape stability in eastern Tasmanian regions, including the study area, due at least in part to a preoccupation with the study of significant Pleistocene cave habitation sites in western and central highland regions of Tasmania. A principal concern of archaeological, paleobotanical and palynological investigation of the Aboriginal occupation has been in establishing a definitive time of their first arrival in Tasmania (Macphail, 1979; Ellis, 1985; Colhoun *et al*., 2010; Fletcher & Thomas, 2010a).

The majority of researchers suggest that according to radiocarbon dating of the oldest known Tasmanian sites of human habitation, Aborigines first arrived at the height of the penultimate glacial period of the present Quaternary ice age, between 38-35,000 years BP (43-40,000 calendar years ago) for example, Breen (2001). The island once more became isolated by marine transgression about 37,000 calendar years ago as the climate began to warm. The next opportunity for further immigration occurred with the next marine retreat during the height of the Last Glacial of the Pleistocene epoch 18,000 years ago. However, although up to 52 Aboriginal quarry and outcrop sites have been recognised across the Tamar and Esk Rivers basin region, the earliest known "major" occupation of the eastern inland, based on archaeological evidence, is dated at about 4,000 years BP (Lourandos, 1968; Jones, 1995).

During the Quaternary glacials, forest was confined to altitudes close to sea level while higher altitudes were covered by grassland, heath, herbfields or were even barren. Landscape stability was particularly vulnerable to fire during dry and windy glacial climates, when vegetation cover was sparse and slow to recover. People periodically or repeatedly occupied caves close to available game, in open country on the central highlands above 400 m elevation, in valleys of the southwest and on a hill that is now Hunter Island in Bass Strait (Flood, 1983; Pike-Tay *et al.*, 2008). Prior to the apparently relatively recent occupation of eastern regions of Tasmania, Aborigines are likely to have exacerbated climate-driven aeolian erosion processes in the west that impacted upon siltation in the Midlands of the Esk Rivers basin (for example Sigleo & Colhoun, 1982; McTainsh, 1989). There is some evidence that Aborigines travelled between the highlands and the southeast coastal lowlands during the Pleistocene (Colhoun, 1984; Ryan, 1996; Cultural Heritage Management Australia, 2010; Paton, 2010), but the inhospitable, arid conditions prevailing across the eastern half of Tasmania precluded its permanent occupation.

While evidence of Aboriginal occupation of the Esk Rivers basin prior to the late Holocene is lacking, northern and eastern Tasmania became more habitable from about

11,000 years BP during the transition from the Last Glacial to the Holocene epoch. Burning was markedly reduced, the cave sites of the southwest were abandoned and the Tasmanian Aborigines adopted a semi-sedentary to nomadic existence over wide rangelands (Lourandos, 1968; Jackson & Brown, 2005). Progressive climatic change saw the translocation of ecosystems that supported game in the Tasmanian landscape. In the early Holocene, there was an altitudinal ascent of vegetation types (Ellis, 1985). Forest vegetation replaced grasslands in a sequence or progression of forest types from *Eucalyptus* to *Eucalyptus*/*Phyllocladus* to *Nothofagus cunninghamii* rainforest. Tasmanian rainforest cover peaked during the warm, humid "Holocene optimum" from approximately 9,000 to 5,000 years B.P. (Colhoun *et al*., 2010). The next major climatic change to cooler, drier conditions about 5,000 years ago was accompanied by notably increased El Niño Southern Oscillation (ENSO) climatic variability, when the eucalypts rapidly expanded once more and rainforests contracted (Prowse & Brook, 2011). These environmental changes undoubtedly challenged hunter-gatherer subsistence (Ellis, 1985), forcing adaptation. However, beyond general inference, hard archaeological or palynological evidence of the Aborigines' response to Holocene environmental changes at local scales has been elusive for researchers, particularly in the Esk Rivers basin. The low resolution offered by pollen and dust/charcoal analysis studies detects regional to extra-regional scale changes rather than local processes and the local effects of people on vegetation (Thomas, 1993; Moss *et al*., 2007).

Nevertheless, research into human prehistory has progressed rapidly in Tasmania over the last 30 years, especially as aided recently by optical (exposure) dating techniques (Colhoun *et al*., 2010). It had earlier been established that the influence of climatic change, seismic activity, the effects of Aboriginal burning and natural catastrophic events were not mutually exclusive causes of landscape instability and erosion (for example Goede, 1973). Consideration continued regarding to what degree Aborigines created (engineered) the Tasmanian Holocene landscape encountered by Europeans 200 years ago. Research began to find support for a view that anthropogenic fire has had the most influence on Tasmania's Holocene vegetation, while acknowledging other agents (Fensham, 1989). Most recently, scholars have reached a consensus that Aborigines used fire for initial engineering then subsequent maintenance of landscape attributes. Aborigines could not have achieved an equilibrium with their environment that sustained resources essential for survival without first causing profound changes to vegetation (Kirkpatrick, 1999).

It cannot be ignored that recent debate has vigorously challenged long-assumed direct links between the timing of Aboriginal dispersal and catastrophic environmental change. Jackson (1999) examined paleaobotanical evidence of a major and sustained vegetation change commencing 70,000 years BP. This was suggested as possible evidence of Aboriginal arrival, occupation and deliberate use of fire, arguing the finding was consistent with concepts of ecological drift and ecological extinction while inconsistent with erosion peaks in the New Zealand (sediment core) climatic record. Referring to the same core record, McIntosh *et al*. (2009) related a sudden three- to fourfold increase in aeolian erosion 40,000 calendar years ago to Aboriginal arrival, occupation and fires. McIntosh *et al.* (2009) argued that the evidence predated the Last Glacial Maximum (LGM) peak in aridity and thinning of vegetation when a climate-driven erosion peak should have been more likely. This event would have occurred during rapid, low amplitude fluctuations in cooling towards the LGM (Colhoun *et al*., 2010). However, these findings (Jackson, 1999; McIntosh *et al.*, 2009) differ from those of a rigorous study that juxtaposed the arrival of Aborigines up to 43,000 calendar years ago with the apparent extinction of the Tasmanian megafauna shortly after (Turney *et al.*, 2008). It was stated firmly that none of the more conventionally accepted evidence of the apparent arrival of Aborigines could be found from that time period, namely a significant increase in burning and an associated shift in vegetation.

Nevertheless, it is certain the present vegetation types and distributions in the lowland west and southwest have been established (metastable) since the LGM. This record is well calibrated across related disciplines, is exclusive of alternative explanations to anthropogenic and is unique to Tasmania (Fletcher & Thomas, 2010a). Before radiating to the eastern half of Tasmania some time during the present (Holocene) interglacial, Aborigines in the southwest lowlands sustained the glacial climate moorlands they were accustomed to using fire. As the climate began to warm, fire prevented the establishment of climax vegetation (rainforest) where climatic and edaphic factors were suitable and where rainforest had established in the previous interglacial in the absence of humans (Colhoun *et al.*, 2010; Fletcher & Thomas, 2010a).

It is clear that Aborigines used fire to engineer an *ecological drift* at a landscape scale, preventing interglacial succession to resource-poor rainforest in the humid southwest (Jackson, 1968; Jackson, 1999; Fletcher & Thomas, 2010b). The temporal resolution of commencement of landscape engineering comes from research across several southwestern Tasmania sites, where burning of vegetation greatly reduced between 15-12,000 years ago before increasing once more from 12-8,000 years ago (albeit to a lesser peak than previously), ending in the early Holocene (Colhoun *et al.*, 2010; Fletcher & Thomas, 2010a). While erosion in the highlands during the latter period led to the aeolian sedimentation recorded in lunette dunes of the Midlands (*sensu* Sigleo & Colhoun, 1982), there appears to be no research evidence of possible landscape scale “engineering” in Tasmania after this time. It seems the vigourous advance of the Tasmanian rainforest during the “Holocene optimum” from approximately 9,000 to 5,000 years B.P. (Colhoun *et al*., 2010) encouraged human adaptation and relocation.

The Aborigines’ subsequent Holocene adoption of a semi-sedentary lifestyle with a range that extended to eastern and northern Tasmania involved much seasonal travel over wide rangelands for resources (Lourandos, 1968; Jones, 1995). In contrast to past maintenance of regional resources to suit a sedentary lifestyle, the primary requirement of a new lifestyle that exploited more extensive rangelands was good communication corridors for efficient travel. Macphail (1979) first observed that Aborigines became adaptive to environmental change from the early Holocene, rather than continually transforming new areas where they ranged. This lack of expansive environmental exploitation is supported by recent research (Colhoun *et al*., 2010; Fletcher & Thomas, 2010a). The nature of pre-European Holocene Aboriginal occupation and its legacy may be further inferred from ethnographic approaches.

Historians and ecologists have long been fascinated by and offered interpretations of the relationship of Aborigines with their environment. Views generally developed from early conceptions of the “noble savage” living in self-sufficient affluence, in harmony with their natural surroundings, to depictions of ruthless Aboriginal “fire-stick farming” completely transforming landscapes (Cosgrove, 1999). In short, Aborigines have been seen variously acting either in conjunct with or overwhelming other agents of environmental change in Australia (Flood, 1983; Breen, 2001; Gammage, 2005). In reviewing the weight of evidence from research into Tasmanian Aboriginal demographics of the late Quaternary period, Lourandos (1997) proposed that the Tasmanian Aborigines led a “flexible subsistence-settlement” existence over their geographical and temporal range, “attuned in some ways to climatic variations through time.” This appears a realistic appraisal of Aborigines having established a steady state in environmental resource management before the time of British settlement.

According to the ethnography of Gammage (2005 & 2011), Aboriginal groups throughout Australia have indeed been farmers, although non-sedentary. Their food was protected from theft or squandering by religious sanction in contrast to protection by strategic defense as occurred in Europe with the development of sedentary farming. Because of maintenance of landscape mosaics by fire, designed to provide suitable settings for hunting and gathering and species habitat niches (for example Jackson & Brown, 2005), food sources were widely dispersed, ensuring greater spatial and temporal predictability and security of resources for Aborigines in spite of climatic cycles of drought and plenty. Long term climatic stressors were anticipated and the resources of an area were never exhausted before moving on (Gammage, 2011).

Of the Esk Rivers basin, it has been well established that local Aboriginal “fire-stick farming” had prevented forest spreading onto the discontinuous grasslands of the Norfolk and Westward Plains in the humid “Northern Districts” (Meander and Macquarie catchments) of the South Esk basin, maintaining a greater abundance and diversity of foods than would otherwise be the case (Flood, 1983; Breen, 2001). Indeed, by the late 19th century, it was remarked that forests were overgrowing the Aboriginal meadows of the humid north, since their regular burnings had been discontinued

(Walker, 1897). Burning was also an important tool in the maintenance of Aboriginal pathways between the “chains of open plains” in the northern Esk Rivers basin lowlands (Walker, 1897; Ryan, 1996; Flood, 1983; Breen, 2001). Aboriginal paths traversed the foot of the Great Western Tiers and from the plains of the Meander catchment to areas they utilised on the Central Plateau (Breen, 2001). The nature of the discontinuous northern lowland plains as Aboriginal artefacts is consistent with patches of meadows maintained in elevated North and South Esk Rivers catchments over about the last 6,000 years (after the Holocene optimum) (Ellis, 1985). However, the effects of anthropogenic fire during this period have been confounded in palynological investigations by a strong climatic signal due to cooler and drier late Holocene climates (Moss *et al*., 2007). It has been suggested that in the northeast highlands, geological and climatic factors perpetuated stable forest-grassland mosaics with (Aboriginal) fire frequency merely a determinant of immediate forest type (Ellis, 1985; Figure 2.2).

The Aboriginal custodians had faced different conditions in the sub-humid Midlands plains. Forests of this region became more open in structure after the Holocene optimum, when dry sclerophyll open-forests and grassy woodlands became established in the rain shadows of both the western and eastern highlands (Gilfedder *et al*., 2003). It is thought that at the time of the arrival of the Europeans, about 500 of an estimated total Tasmanian Aboriginal population of 5,000 to 7,000 lived in the Tamar basin (Kirkpatrick & Bridle, 2005). In the north of the basin lived the Port Dalrymple tribe, in the South Esk valley the Ben Lomond tribe, and in the Midlands the Stony Creek tribe (Walker, 1897). The open grassy woodlands and meadows (savannah) that covered most of the Midlands plains at the time of European settlement between the present

Figure 2.2: "Patches of meadows:" Aboriginal cultural landscape of disclimax vegetation, upper South Esk catchment, northeast highlands.

sites of Launceston and Tunbridge (near Oatlands) have conventionally been regarded as artefacts of Aboriginal occupation and firing (Fensham, 1989). However, from experimental results, Fensham and Kirkpatrick (1992) suggest the ecosystems and landscape of the plains may have been continually extant since the Last Glacial (before Aboriginal occupation), based on competitive exclusion of tree seedlings by grass swards and root mats. Further experimentation confirmed earlier suggestions that the influence of fire in maintaining grassy ecosystems was less important than the degree of grazing pressure by both native and exotic herbivores, frost prevalence and drought-fire and frost-fire interactions (Kirkpatrick & Bridle, 2007). The findings were similar to those of Ellis (1985) who found that the longer the northeast plateaux sites are occupied by grasses, the less favourable the soil is for the establishment of eucalypt seedlings.

No doubt further evidence relating to Aboriginal occupation in the Esk Rivers basin will be unearthed over time. A lack of juxtaposed archaeological and charcoal evidence in the literature cannot rule out Aboriginal occupation of the basin earlier than late Holocene. Nevertheless, the overall weight of existing evidence suggests that Aboriginal fire management in the region was applied at local scales, rather than extensively, and furthermore, that fire was used for landscape maintenance rather than ongoing expansive landscape engineering. Indeed, much of the open grassy woodland country encountered by the Europeans in the Esk Rivers basin may not be an Aboriginal artifact; these areas may not have required maintenance by fire at all (Fensham & Kirkpatrick, 1992).

2.3 Tamar estuary siltation: historical background from British colony to 21st century

2.3.1 Early settlement: the first 50 years

British colonists arrived in Tasmania in 1803. In the course of British discovery and early exploration of the Tamar estuary and the Esk rivers, they encountered a landscape sparsely occupied by Aborigines (MacKnight, 1998). The suitability of the land for grazing settlement was evident to the first explorers from the “pasturage” and grassy tracts seen along the estuary and on nearby coastal reaches. Further inland from the head of the estuary, thousands of acres of extensive plains of rich luxuriant grass with small lagoons were reported by the first explorers (MacKnight, 1998).

The more open country around the sites of Hobart and Launceston, and the Midlands between them, were rapidly explored and colonised (Lakin, 1967; Morgan, 1992). Settlement was established in the Hobart area from 1803 and at Port Dalrymple from 1804. The British had traversed the overland route between these two settlements by 1811 (Newitt, 1988). "Port Dalrymple," in early historical records of the colony, denoted the Tamar estuary and surrounding environs, from the mouth of the estuary to its head, including the area of the early land grants on the plains of the South and North Esk Rivers (Pretyman, 1950-70). While the Tamar was initially settled near its mouth, there were better prospects for agriculture at the head of the estuary, so the principal settlement was moved to the present site of Launceston in March 1806 (Lakin, 1967). Agriculture grew swiftly.

Initially, small lots of land were granted to soldiers and time-expired convicts and larger lots to officers and officials. To encourage enterprise, as in other colonies in Australia, grants were next made to *bona fide* settlers under explicit direction to clear and cultivate the land, on promise of a later nominal payment (a "quit-rent"), conditions apparently often not enforced (Morgan, 1992). The first such grant in northern Tasmania was 1,000 acres on the South Esk in 1808, but this was not the first land occupied in the Esk Rivers basin. Many settlers moved onto land and commenced development before their grants were registered. Much of Launceston's hinterland was thinly wooded and easily settled for agriculture. Indeed, in comparing Launceston to the "principal agricultural settlement in New South Wales," a 1810 report by Oxley stated that 100 acres could be cleared in the same or less time than 20 acres in NSW (Bethell, 1980).

The main priority of the first settlers on the Derwent (Hobart Town) and the Tamar was to avoid starvation (Lakin, 1967). However, primary production rapidly grew from subsistence level to export capacity within the first two decades of the Tasmanian colony's history. By 1820, wheat had become an important export crop and almost 283 km^2 of land close to the two centres had been granted for settlement. Between 1815 and 1820, a total of 60,309 bushels of wheat were exported to NSW from Hobart and 47,355 from Port Dalrymple (Morgan, 1992). Then in 1822 alone, 61,072 bushels were exported from the colony of Tasmania. Thus, within only 19 years after first settlement, all of the most accessible land of the Esk Rivers basin had been granted to colonial settlers who lacked expertise in the long term productive capacity of this foreign land and its resilience to change (Morgan, 1992). Once wool was successfully exported in the early 1820s, demand arose for larger holdings and the annual alienation of Crown land (the passing of land tenure in the colony from vestment in the name of the sovereign state to private hands) by grant increased rapidly (Lakin, 1967). Tasmania-wide, Crown land alienated by grant reached an aggregate of 4,047 km^2 by 1825.

While forests and woodlands of the Tamar basin were being cleared for farming land, pre-existing fire regimes established by the Aborigines were altered, changing forest types and destabilising landscapes around settlement areas. The severity and extent of bushfires, often deliberately lit, was lamented by colonial commentators (Morgan, 1992). The establishment of introduced grasses further increased the risk of bushfires, since they have heavier fuel loads and dry out earlier in the summer season than native grasses (Thomas, 1992 in Kirkpatrick & Bridle, 2007). Ellis (1985) wrote of how the Tamar catchment in northeast Tasmania was transformed by greater fire frequency and severity in the mid 1830s during the transition from Aboriginal management to settler land use. This compared with the Aborigines' prior maintenance of vegetation attributes in a steady state since the mid-Holocene (2.1.2). The collection of wattle bark for skin-tanning was an important export to England from 1820 and made a substantial impact on the landscape (Morgan, 1992). In the early days, trees that had been stripped of their bark stood where they had died (Breen, 2001). Later, plantations or regrowth of wattle were used (Morgan, 1992).

The environment the settlers and their labourers were working in was more alien than that encountered in other British colonies (Morgan, 1992). More than this, they came from a range of backgrounds prior to taking up life on the land in Tasmania. Those who actually possessed farming skills had worked fertile lands established for centuries in their homeland. Moreover, the British were unprepared for a climatic regime where the ravages of drought and fire are typically followed by flooding rains. It is not surprising that a certain ineptitude in the development and management of colonial lands was evident, with many early attempts to transform the place into an "antipodean England" ending in severe agricultural failure and environmental degradation (Morgan, 1992). Riparian vegetation was cleared and hydrological regimes altered. It has been suggested that an increased prevalence of floods in the late 1820s was due to the practice of clearing land on river banks by pushing the logs into the river, forming temporary, unstable dams (Morgan, 1992).

Much of the greater "Northern District" west and southwest of Launceston in the Esk Rivers basin, areas known then as Norfolk Plains and the Westward respectively, was settled by 1854 (Breen, 2001). While in most world rivers, erosion and sediment flux increased in the early 1900s (Syvitski & Kettner, 2011), it may have occurred earlier in the Tamar basin. It is apparent that the initial 50 year period of colonisation was associated with rapid and substantial landscape change.

2.3.2 Land use, erosion and siltation management from the mid 19th century

Dredging of the upper Tamar estuary (Home Reach) to improve access for vessels to wharves at the port of Launceston was first undertaken as early as 1859, although dredging of the main channel did not commence until *ca* 1920 (Foster *et al.*, 1986; Hydro Tasmania, 2003). By interpreting historical surveys, Foster *et al.* (1986) found that at any particular location along the lower estuary up to 1914, *long-term* cross-sections were essentially constant, although subject to *short-term* variation in a *regime* of siltation and scour according to prevailing conditions. Left to itself however, the Tamar estuary would ultimately infill with sediment top-down, as part of the natural evolution of a drowned river valley becoming an alluvial valley (Foster *et al.*, 1986; Pirzl & Coughanowr, 1997; BMT WBM Pty Ltd, 2008; Gunawardana & Locatelli, 2008; BMT WBM Pty Ltd, 2010). As suggested below, industrialisation across the catchments most likely accelerated the evolution.

It was an increase in wool export demand from the 1820s to the 1850s that drove a rapid expansion of pastoralism from the hinterlands of the two ports into the Midlands, Tasmania's largest sheep-growing district. By the mid 1850s, carrying capacity had been reached or exceeded (Morgan, 1992; Kirkpatrick & Bridle, 2007). Rabbit plagues and poor sheep husbandry saw depletion of palatable native grasses on the grazing selections by the 1880s. Due to the lack of fences, the sheep kept moving onto adjoining grasslands and preferentially grazed and degraded north-facing slopes where the soils eroded (Kirkpatrick & Bridle, 2007). It was a wave of landscape destabilisation.

The rural economy received a major boost from timber and agricultural export earnings with the mid-1850s great Australian gold rushes. By 1855, a botanist on a coach journey from Launceston to Deloraine in the Meander catchment commented that the trees of the previously dense forests between the grassy plains “had in most places been thinned and in many completely cleared” (Breen, 2001). Consequent to the Australian gold rushes, when the population of Australia quintupled in 20 years (Australian Bureau of Statistics, 1910), and the end of the colonial period with the loss of convict labour in 1853, private enterprise struggled through a period of economic depression (N. Haygarth, pers. comm., 2011). However, the agricultural economy expanded during the later 19th century, as the Waste Lands Acts (1858-1870) encouraged settlement of land more distant from the port of Launceston and/or more heavily timbered, particularly smallholdings. Thus, settlement expanded into bushland fringing established estates in the study basin, including districts such as Deloraine, Liffey and Blessington in the Meander and North Esk catchments (Breen, 2001). However, much of this land was quickly cleared of timber then abandoned. Indeed, several high impact, extensive bushfires were documented throughout the Esk Rivers basin during this phase of colonisation (Ellis, 1985; Morgan, 1992). The Waste Lands Acts period, characterised by the loss of forest cover on the fringes of settlement and over the high rainfall topography of the catchments, represented the second wave of landscape destabilisation imposed by the settlers.

However, the fire regime in the northeast highland landscape changed once more at the turn of the century. Fires were generally of less intensity and frequency than earlier in colonisation, mainly confined to grazing leases (Ellis, 1985). In response, the vegetation types of the northeast highlands of the Tamar basin moved toward climax. Rainforest expanded into previous eucalypt forest, and eucalypt forest into areas of grassland that even earlier had been rainforest, prior to a devastating fire of the previous century. Then a major fire in 1908, probably associated with gold and tin mining, burned extensive areas of the upper South Esk catchment, increasing the area of plains over and above the previous extent of Aboriginal artifacts (Ellis, 1985; Figure 2.3).

2.3.3 Mining

Several quartz lode (reef) gold mines operated in the South Esk headwaters from 1852 according to Department of Mines Geological Survey Bulletins of 1907 and 1935, with activity peaking by the early 1880s (Twelvetrees, 1907; Finucane, 1935). Most had closed by the early 1930s (Preston, 2011). Significantly, over the course of the gold mining boom, many individual prospectors thoroughly worked and reworked the alluvium along the tributaries of the South Esk River near Mathinna (Twelvetrees, 1907). Such activities may have had the most environmental impact of all the mining activities in the study basin. According to the Year Book of Australia, 1911 (Australian Bureau of Statistics, 1910) more alluvial gold was won (329 oz.) in Tasmania's northeast than reef gold (219 oz.). Coal mining began near Fingal in the Break O'Day sub-catchment in the upper South Esk catchment in 1864 and continues today, as the only extant coal mine in Tasmania (Bacon & Banks, 1989).

Two major tin and tungsten mines operated at Rossarden in the South Esk catchment between 1892 and 1982 (Pirzl & Coughanowr, 1997; Aquenal Pty Ltd & Department of Environment, 2008). The tailings from these mines were discharged directly into the South Esk tributaries of Storys and Aberfoyle creeks until 1959, when settling ponds for the fine tailings came into use. The principal concern arising from this legacy has been ongoing elevated concentrations of heavy metals that are present in downstream floodplains and are carried mainly in the dissolved load for the remaining 130 km length of the South Esk River to the Tamar estuary (Norris *et al.*, 1980; Norris *et al.*, 1981). The long term effects of the mining on erosion and sedimentation are unknown.

2.3.4 Droughts, sheep and forestry of the 20th century

Grazing lands of the Midlands suffered from the first of two historical long dry periods, from the mid 1890s until the mid 1910s. Droughts between 1908 and 1910 and again in 1914 were so devastating that severe crop and stock losses occurred in almost all agricultural areas (Lakin, 1967). The effects of these droughts and overstocking during drought represent a third wave of landscape destabilisation since British colonisation. It is arguable that coming so soon on the heels of the second wave (Waste Lands Acts 1858-70), with little respite during which landscape elements could reach a new equilibrium, a prolonged period of instability was sustained for over 50 years since the Waste Lands Acts first came into affect.

While Crown lands were important for grazing in the first century of settlement, as more land was alienated forestry use of Crown lands began to exceed grazing use early in the 20th century. Crown lands dedicated for forestry, which covered 2,127 km^2 of Tasmania in 1890, increased to 4,037 km^2 in 1910 (Lakin, 1967). A major increase in demand for forestry products (pulpwood) from northern Tasmania including within the study catchments came in 1938 when the Burnie paper mill was established, followed by the Boyer newsprint mill. Tasmania-wide dedication of Crown lands for forestry increased from 6,519 km^2 in 1940 to 14,210 km^2 in 1964 (Lakin, 1967).

Sheep farming in the sub-humid Midlands in the 20th century continued to act in concert with (or in defiance of) climatic extremes to exact an environmental toll (Kirkpatrick & Bridle, 2007). Severe droughts of shorter duration than in the 1910s were recorded in 1945 to 1946 and again in 1951 to 1954, when hydro-electric power had to be rationed. The wool industry had fluctuated for a century following a peak in the 1850s. Then there was a resurgence in the mid 20th century, when breeding for quality, better land management, new technology and high wool prices due to demand with the Korean War led to further clearance of large areas of native vegetation for improved pasture establishment (Morgan, 1992; N. Haygarth, pers. comm., 2011).

The second (still extant) historical long dry period in the Midlands grazing lands commenced in 1978 with a drought that was more severe than the 1910s drought, and heralded significant climatic change (Kirkpatrick & Bridle, 2007). Most lone trees that survived the 1910s drought died. Woodland remnants declined in health due to lack of native shrub and litter understorey, exotic pasture species and grazing (Davidson *et al.*, 2007). By 1989, only 17% of the Midlands' pre-European native vegetation of grasslands and grassy woodlands remained, just 170 years after settlement (Fensham, 1989). By the mid 1990s, wind erosion of dry pasture soils of the Macquarie and South

Esk catchments was widely regarded as the greatest cause of soil loss in these low rainfall regions (Bobbi *et al*., 1996). Many of the wetlands and lunette lakes that the early settlers encountered in the Midlands have dried up in recent decades. An apparent subsequent decline in erosion rates in the Midlands more recently is consistent with not only establishment of a new equilibrium due to recovery of the vegetation cover with hardier native and introduced vegetation becoming established, but could also be explained by depletion of lighter surface sediment available for transportation (Kirkpatrick & Bridle, 2007).

Coinciding with the onset of dry conditions in the 1970s, further woodland and forest was cleared in the Midlands, feasible because of demand for logs upon commencement of the export woodchip industry (Kirkpatrick & Dickinson, 1982; Kirkpatrick & Bridle, 2007). Woodchip exporting began in Tasmania in 1971, with up to 2 million tonnes per annum processed and dispatched (Kirkpatrick & Dickinson, 1982). Within three years of the commencement of the export industry in Tasmania, the volume of wood being cut in Tasmania's forests doubled and forests were being clearfelled at a rate of 150 km^2 per year (Kirkpatrick & Dickinson, 1982). In addition to the clearance of privately owned dry forests, especially in the Midlands, Crown land forestry concessions increased to 15,547 km^2 by 1985 (Lakin, 1967; Cocking, 1985). Native forest communities were transformed ecologically, extending the eucalypt/grass and eucalypt/tea-tree vegetation types at the expense of wet forest types (Kirkpatrick, 1991). Thus, sheep grazing impacts as well as the loss and transformation of native vegetation with sudden expansion of industrial scale forestry (from the 1970s) represented a fourth wave of landscape destabilisation since British settlement.

2.4 Post-industrial era silt studies and the commencement of coordinated land degradation mitigation

Regular dredging of the main channel of the upper Tamar estuary between 1949 and 1960 removed an average of 180,000 m^3 of silt per annum, resulting in subsequent rapid sedimentation rates as the estuary channel returned towards pre-dredging regime equilibrium (Aquenal Pty Ltd & Department of Environment, 2008; BMT WBM Pty Ltd, 2008). Foster *et al.* (1986) estimated a siltation rate of about 100,000 m^3 per annum until the Trevallyn/Poatina hydro-electric Power Scheme was commissioned in 1955. While the small Trevallyn Dam intercepted river bedload, it was found to have no significant effect on flows or suspended sediments entering the estuary during floods (Foster, 1986). Nevertheless, augmentation of flows using water diverted via Poatina from the upper Derwent River catchment on the Central Plateau reduced the incidence of low flows entering the estuary from the South Esk River, improving the flushing of the upper estuary and so reducing siltation to about 30,000 m^3 (43,300 t) per annum at Home Reach. However, regular dredging had ceased by 1966, when major seaport activities were relocated to the lower estuary.

Dredging activities from 1920 to the mid-1960s maintained the upper estuary channel at dimensions larger than those previously or since. Historical (1889-1984) and recent (2006-13) cross-sections of Kings Wharf in Home Reach (ID: 18A; location, Figure 2.3) are compared in Figures 2.4 and 2.5. The historical and recent survey datums (x-axes) are consistent. However, note that the cross-sections have been drawn as if facing upstream on the location map (E-W, right to left).

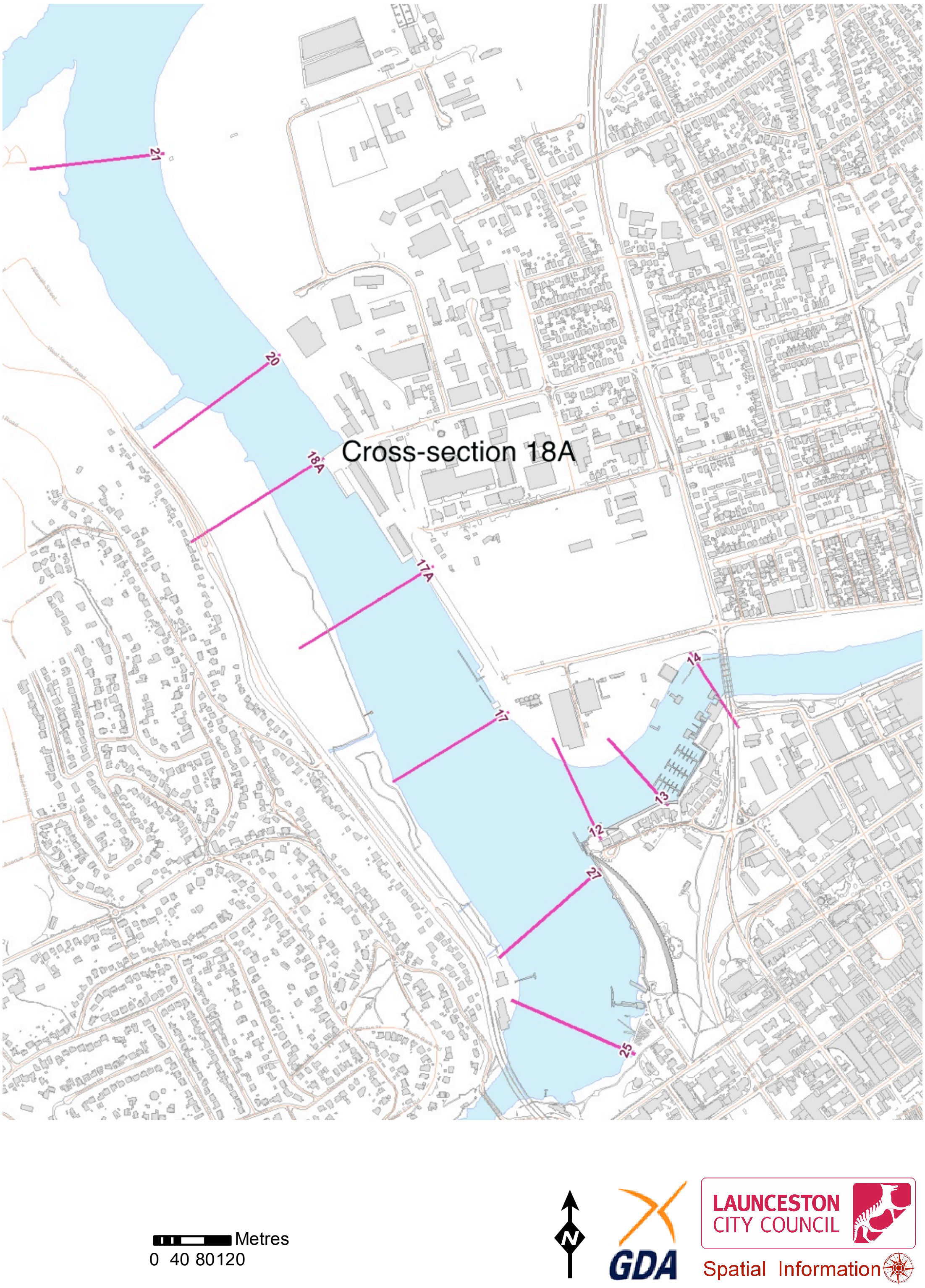
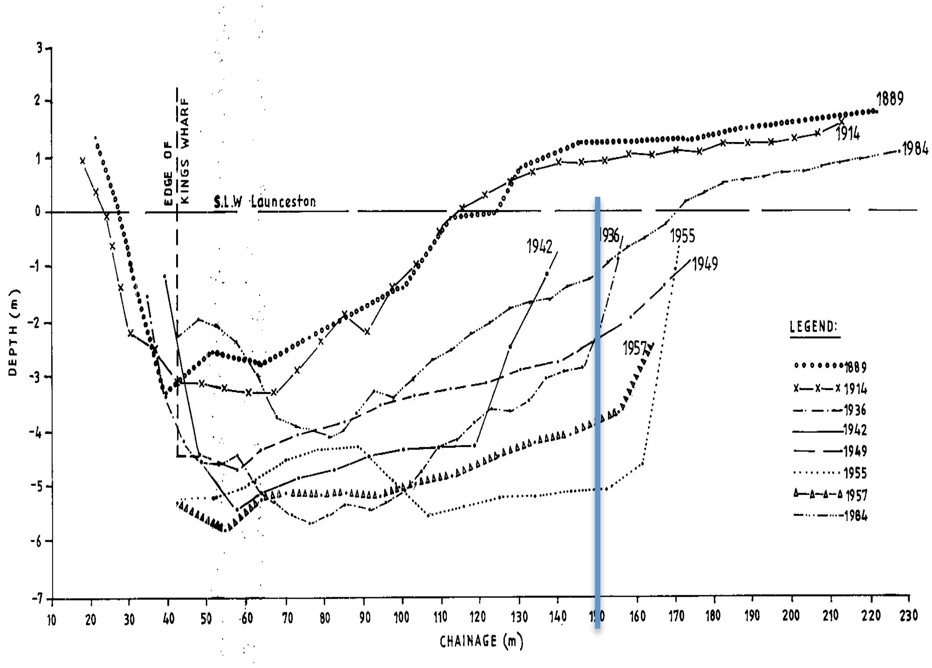
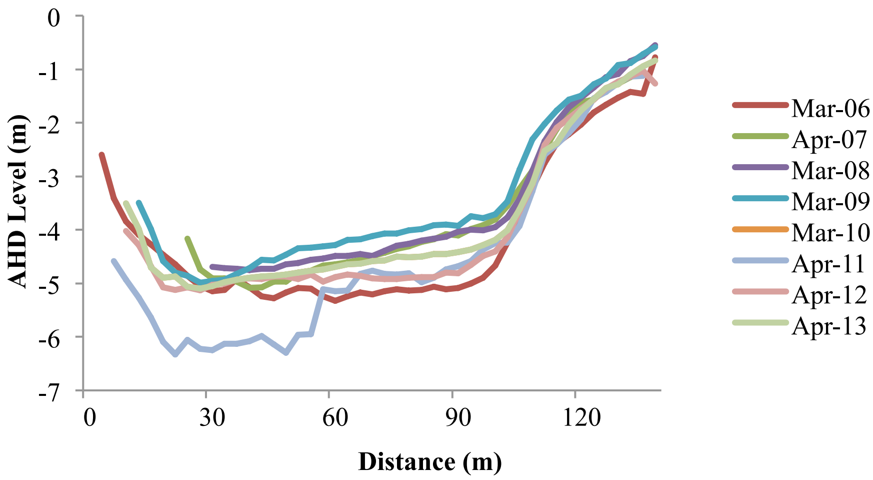


Figure 2.3: Location of Kings Wharf channel cross-sections (example 18A), Home Reach, Launceston. The South Esk River enters the Tamar estuary bottom, centre; the North Esk River enters on the right. Source: BMT WBM (2010), used by permission of Launceston City Council and Launceston Flood Authority.



E W

Figure 2.4: Historical Kings Wharf channel cross-section (18A), Home Reach (1889-1984). Location: see Figure 2.3. The blue vertical line indicates the approximate westerly extent of the recent cross-section series below. Reproduced from Foster *et al.* (1986), used by permission of Launceston City Council and Launceston Flood Authority.



E W

Figure 2.5: Recent Kings Wharf channel cross-section (18A), Home Reach (2006-13). Location: see Figure 2.3. The chart is scaled and positioned for direct visual comparison with Figure 2.4 above. Data supplied by Launceston City Council and Launceston Flood Authority.

The regime equilibrium condition of the channel at Kings Wharf is shown in the cross-sections of 1889 and 1914, topmost in Figure 2.4, when the navigable channel width was limited, and the maximum depth (with respect to *SLW*, Launceston) was approximately 3.5 m (Foster *et al*., 1986). Since then, dredging activities increased the channel dimensions to the maximum shown in Figure 2.4 (cross-sections for 1955-57), when the channel was approximately three times the regime dimension. Return towards regime conditions from reduced dredging is evident in 1984 and later cross-sections (Figure 2.5). Dredging sites functioning as repositories for rapid siltation is also illustrated, for example where a dredged depth shown under Kings Wharf in the April 2011 cross-section refilled by April 2012. From annual to tri-annual cross-sections during the interim period from 1985-2005 (not shown), a more extensive volume of silt removed to 4 m under Kings Wharf in October 1994 refilled by April 1998 (BMT WBM Pty Ltd, 2008).

While catchment basis suspended sediment flux estimates from the *WaterCAST* modeling of 2008 (Chapter 1) appeared conservative when compared with literature values primarily sourced from studies elsewhere in Australia (BMT WBM Pty Ltd, 2010), the *WaterCAST* findings, enhanced by additional data to 2015 (Tamar Estuary and Esk Rivers Program, 2015) suggested contemporary annual sediment flux from the Esk Rivers basin to the Tamar estuary had increased to about 2.5 times that estimated for the pre-European Holocene period, from 31,500 t to 74,722 t (annual average).

The suspended sediment modeling by land use was summarised in Chapter 1 (BMT WBM Pty Ltd, 2010; Tamar Estuary and Esk Rivers Program, 2015). It was found that conservation land use yielded 26% for 24% of land area. Steeply sloping, high elevation and rainfall locations adequately explain this sediment yield from largely undeveloped land. Indeed, it is surprising that these dominantly alpine areas are not delivering more sediment as a lingering post-glacial legacy (Syvitski & Kettner, 2011), suggesting that a relative equilibrium has been reached. Low slope gradient, low rainfall locations partly explains the low sediment yield from agricultural land (26% for 48% land area), together with depletion of transportable material in early severe erosion on the sheep runs (Kirkpatrick & Bridle, 2007). In contrast, forestry that dominantly occupies the sub-alpine regions and midslopes delivered 38% of the sediment for 24% of the land area.

Plantation forestry, a part of the contemporary forestry mix, has shorter rotations between harvest disturbance than native forests, and requires mechanical cultivation to establish each crop. Supported by the financial incentives of Managed Investment Schemes (MISs), plantations on private and public land expanded following the "Plantations for Australia: The 2020 Vision" initiative of the Australian government in 1997 (Thompson, 2009; Forest Practices Authority, 2012). However, less than a decade later, plantations were compromising ecosystem services across the landscape, causing increasing concern.

Available catchment-based statistical data for plantations are limited to one snapshot of plantations on private land at 2006 (Private Forests Tasmania, 2007). At this time, privately owned plantations covered 227 km^2 (2%) of the Esk Rivers basin and represented 8.9% of the total Tasmanian coverage (Figure 2.6).

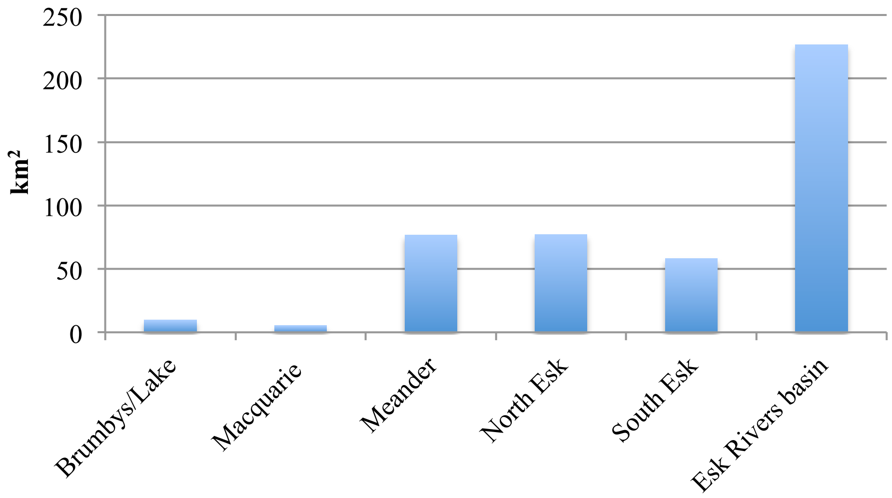


Figure 2.6: Private land plantation estate (2006) by Esk rivers catchments and total basin. Source: Private Forests Tasmania, 2007. The extent of public land plantations at this time is not known.

Over the late 20th century, when forestry plantations were being established largely at the expense of native forests, community groups argued for cessation of this displacement (Green, 2004). However, the first decade of the 21st century saw rapid expansion of the plantation industry across land tenures, increasingly replacing farming land, displacing rural families and communities and reducing dissent. Plantations were being located mostly in higher rainfall regions of northwest, northern and northeastern Tasmania, proximal to the mills and ports. Expansion of plantations by replacement of native forest was phased out between 2006-2011 (Forest Practices Authority, 2012; Fitzgerald & Dudley, 2015). However, the dominant political power and financial hold of Gunns Limited, proponent of a world-scale pulp mill, did not collapse until the period 2008-2012 (Beresford, 2015). This period marked the failure of a pulp mill and of the company that proposed it. This is important to the present study because over decades of political and economic hegemony, Gunns Limited drove plantation expansion in Tasmania, now featuring strongly in the landscape of the study catchment.

Since British colonisation, change in the landscape has been rapid and destabilising. Destabilising processes imposed included 1. rapid land use conversions, 2. forest clearance, 3. extensive bushfires 4. clearance of riparian zone vegetation and 5. overstocking grazing land. Erosion is an inevitable consequence of the loss of vegetation cover due to such processes.

2.5 Climate futures and erosion

It is apparent that erosion may be enhanced when anthropogenic and climatic drivers combine. While knowledge and expertise in environmental management have improved, the advent of rapid anthropogenic climate change casts uncertainty over the stabilisation of landscapes towards a future equilibrium (Grose *et al.*, 2010; Syvitski & Kettner, 2011). There is increasing awareness of the need to integrate regional land management actions to address anthropogenic climate change adaptation in the Esk Rivers basin across increasing frequency and severity in cycles of drought and flood.

The main affect of moisture deficit during drought years is to exacerbate Tasmania's dry summer-autumn period when evapotranspiration rates are high. Exposure of less permeable clay subsoils and compaction of soils decreases water infiltration rates, increasing drought stress. Flooding rains that follow droughts erode stream banks that lack riparian vegetation due to clearance and free access by livestock (Bobbi *et al.*, 1996). Overstocking in wet winter conditions has been shown to reduce infiltration, resulting in increased runoff and erosion, exacerbated by slow pasture recovery because of slow grass growing rates in winter (Elliot & Carlson, 2004). Furthermore, the most common soils of the Midlands, duplex soils of sandy loam over clay and deep sands, have been shown to be vulnerable to wind and tunnel erosion if ploughed (Grose & Moreton, 1996).

Changes to sediment flux are likely to continue, as parts of the landscape already vulnerable to erosion are already experiencing changes in total annual precipitation, temporal distribution and changes in runoff (for example Campbell, 2008; Prowse & Brook, 2011). Tasmania's northeast, historically subject to variable rainfall and high magnitude events, will experience up to 25% more high intensity rainfall events (White *et al.*, 2010).

Research suggests sediment loads from landscape disturbance in high rainfall upper catchments will further increase as climatic stressors increase (Davies *et al.*, 2005; BMT WBM Pty Ltd, 2010). However, perhaps because of food production and export imperatives as much as a strong expertise in land management for food production, resources are more focused on future scenario modeling and improving environmental management for agriculture than for upper catchment land uses (Tamar Estuary and Esk Rivers Program, 2015).

The nature of NRM North's recent work to support profound improvements in land management practices including stream rehabilitation was introduced in Chapter 1 (Tamar Estuary and Esk Rivers Program, 2015). NRM North recognises the imperative to control erosion in the context of anthropogenic climate change. It is possible that primary production has reached its peak and may decline without substantial and immediate land management improvements (Grose *et al.*, 2010).

2.6 Summary

Climatic drivers of erosion have been significant. Destabilising glacial-interglacial oscillations of increasing amplitude occurred over the 5 Ma before people arrived in Tasmania during the last glacial period. Much of the supply of sediment to the Esk Rivers basin during the two glacial periods prior to the Holocene epoch may be confidently attributed to climate-driven erosion processes, with aeolian sedimentation enhanced by Aboriginal fire-stick landscape management in western Tasmania.

From the evidence, Aborigines dispersed to Tasmania during the penultimate glacial of the present Quaternary ice age at least 37,000 years ago. They widely engineered coastal landscapes of the humid southwest by fire, as they had previously on the Australian mainland, preventing the vegetation climax to rainforest. Any Aboriginal fire in arid regions (for example in the central highlands) would have enhanced climate-driven landscape instability during prevailing dry, cold and windy glacial conditions, causing aeolian (wind-blown) erosion events affecting the study region. However, from the evidence, pre-British colonial sediment flux did not peak until the Pleistocene-Holocene transition 11,000-8,000 years ago, comprised of a ready supply of highland sediments made available for fluvial transport by glacial and periglacial processes.

The next major climate-driven erosion period commenced 5,000 years ago, with a change to cooler, drier and fluctuating climatic conditions. However, less sediment was available for transport than during transition to the Holocene climate. Since the arrival of Aborigines in the Esk Rivers basin in the late Holocene (*circa* 4,000 years ago to current knowledge), Aboriginal land management by fire appears to have been widespread but localised and not expansive. Fire was used in the maintenance of pathways and discontinuous grassy plains and meadows. The British colonists likely encountered a landscape in a condition of dynamic steady state, a state of minor oscillations in environmental stability.

In contrast to the Aborigines, the British colonists precipitated an era of rapid landscape change as they established sedentary farming practices and continued to geographically expand and intensify their influence. The areal scale of British occupation had eclipsed that of the Aborigines within two decades of their arrival. From historical accounts, the settlers demonstrated a degree of ineptitude in management of the alien environment of their new home and failed to adopt sustainable stocking densities and appropriate land management practices in anticipation of inevitable drought years.

A profound and rapid landscape change accompanied the industrialisation of the basin, promoting erosion processes and exacerbating the effects of regional cyclic drought and flood. Sources of enhanced suspended sediment load in Tamar basin rivers include upper catchments, sediment remobilised from floodplains (Collins *et al.*, 1997b) and from historical alluvial mining in the upper South Esk River valley (Preston, 2011). It is likely siltation in the Tamar estuary increased above pre-European settlement rates as has sediment flux in most world rivers, the timing coinciding with industrialisation in the early 1900s (Syvitski & Kettner, 2011). Episodes of landscape destabilisation contributing to erosion and sedimentation are presented in Table 2.1.

Table 2.1: Major landscape destabilisation events and processes identified by the review (continued overleaf).

Calendar years ago	Geologic time	Event (location if not whole Tasmania)	Erosion/instability processes	Reference
5 Ma to 14,000	Pliocene-Pleistocene ice ages	Glacial-interglacial oscillations of increasing frequency	Glacial and peri-glacial mass movement and weathering; cycles of aridity; denudation of dolerite; generation of plentiful weathered material for erosion	Hill (1990); Kershaw *et al.* (2003); Jackson (2005)
		Rainy season changes from summer to winter, causing summer droughts and greater aridity	Annual wet-dry cycles; vegetation redistributions; widespread frost; aeolian dunes form in the Midlands	Hill (1990); Jackson (2005)
60-50,000		OIS 4[1] transition to last interglacial	Inferred aeolian erosion event	CHMA (2010)
From 40,000 (OIS3)[1]	Last Glacial Maximum	Aborigines arrive; landscape management by fire likely post-dated LGM, probably local in scale (southwest lowlands, western valleys and central highlands)	Vegetation cover waxes and wanes with fluctuations in temperature and Aboriginal fire; periglacial erosion; evidence of Aboriginal occupation 37,500 years ago (no evidence north or east)	Turney *et al*. (2008); Colhoun *et al*. (2010); CHMA (2010); Fletcher & Thomas (2010a); Paton (2010)
35-15,000 (OIS2)[1]	LGM to Pleistocene/ Holocene transition	Aridity became more extreme in east; Aborigines managed central landscapes and engineered moorland landscapes where vegetation climaxed to rainforest in previous interglacials (west)	Aboriginal fire reduced vegetation cover (central highlands and pathways to southeast) and climate-driven reduction in vegetation cover in the east enhanced erosion. Concentrated periglacial activity 23-16,000 years ago	Cosgrove (1999); Turney *et al.* (2008); Williams *et al.* (2009); Colhoun *et al*. (2010); Fletcher & Thomas (2010a & 2010b)
15-8,000		Burning reduced 15-12,000 years ago; increased 12-8,000 years; SW caves abandoned 13,000 years ago	Climate change; less destabilisation by fire than post-LGM	Colhoun (1984); Jackson & Brown (2005); Colhoun *et al*. (2010); Fletcher & Thomas (2010a)
9,500 to 9,000	Early Holocene	Aeolian dispersal of weathered material; reduced burning, but climate-driven erosion	Aborigines have adopted a semi-sedentary lifestyle; local scale landscape maintenance by fire. Aboriginal fire, changing climate and vegetation	

[1]OIS: oxygen isotope stages, interchangeable with MIS: marine isotope stages.

Table 2.1: Major landscape destabilisation events and processes identified by the review (continued).

Calendar years ago	Geologic time	Event (location)	Erosion/instability process	Reference
4,000	Late Holocene (post-Holocene maximum) a) Aboriginal influence	Aborigines have dispersed from western to eastern Tasmania including Esk Rivers basin	Earliest archaeological evidence of occupation of northern and eastern inland; local scale landscape maintenance by fire	Lourandos (1968); Jones (1995); Jackson (1999)
4,440 to 1,490		Aeolian dispersal of weathered material	Aboriginal fire (less than early Holocene); changes to climate (cooler, drier) and vegetation (> sclerophyll)	Colhoun (1984); Macphail (1979); Ellis (1985); Fensham & Kirkpatrick (1992); Lourandos (1997)
4,000 to early 1800s		Occupation of engineered landscapes	Maintenance of landscapes previously engineered; increased El Niño Southern Oscillation (ENSO) variability	
1804-25	Late Holocene (post-Holocene maximum) b) European occupation	British agri. development (Esk Rivers basin)[2]	Rapid transformation of grasslands and sclerophyll woodlands by grazing and cropping; forest clearance and extensive fires	Fensham (1989); Morgan (1992); Jackson (1999)
1858-80s		Waste Lands Acts[2]	Rapid native vegetation clearance at margins of the estates	Scott (1965); Breen (2001)
1852-1930s		Upper South Esk gold rush	Several commercial mines in operation; individual prospectors working and reworking alluvium	Preston (2011)
1890s-1910s		Poor sheep husbandry; drought[2]	Overstocking of grazing land in the sub-humid Midlands combined with drought; loss of tree vegetation and ground cover	Kirkpatrick & Bridle (2007)
1971 onwards		Export woodchip industry; ongoing industrial scale forestry[2]	Industrial scale clearfelling of forests in upper catchments; financial incentive for further clearance of woodlands and forests marginal to grazing land in the Midlands	Kirkpatrick & Dickinson (1982); Kirkpatrick (1991)
1975 onwards		Onset of long term decline in precipitation	Overstocking of grazing land in Midlands combined with drought; widespread tree death and loss of ground cover	Kirkpatrick & Bridle (2007)
~1800 onwards	Anthropocene	Global earth surface and hydrologic engineering; forcing of climate change	Sediment flux signal defines Anthropocene; more frequent extreme weather events, longer summer-autumn droughts and vegetation translocation with anthropogenic climate change	Grose *et al*. (2010); Syvitski & Kettner (2011)

[2]Sequence of historical "waves of landscape destabilisation"

The sediment flux determinations of Foster *et al*. (1986) and BMT WBM (2010) were in reasonable proximation, suggesting flux had levelled out. However, it is apparent that the otherwise apparently globally ubiquitous reversal during the 1950s of the anthropogenic sediment signal to below "pristine" levels, due to entrapment of sediment by dams, did not occur in the Tamar estuary because of the dominance of fine clays (Foster *et al*., 1986) in the sediment load. These fines remain in suspension, avoiding entrapment in Trevallyn Dam. It is possible that a portion of these fines is present as a delayed response to profound Pleistocene glacial and periglacial processes (Svitski & Kettner, 2011), with a further portion being mobilised by land use changes in the catchment hinterlands where soils had been previously stabilised by vegetation cover earlier in the Holocene.

NRM bodies have been identified as having a key role in adaptation to climate change although their environmental programs will need to be intensified (Campbell, 2008). As already identified in Australia's regional NRM plans, vegetation/land cover management will be critical to future soil conservation and maintenance of landscape functions. Management measures to optimise landscape resilience include preventing poorly planned clearing and overgrazing of native vegetation and in encouraging restoration of vegetation cover in over-cleared landscapes (Campbell, 2008). Works in Tasmania include programs on private land in the Midlands for example the Protected Areas on Private Land (PAPL) program (Tasmanian Land Conservancy, 2013) and the Midlands Conservation Fund (Hanson, 2013, June 7-13).

The first objective of this study, to synthesise a background on landscape evolution and stability over recent geological time and to qualitatively relate erosion and erosion processes in the present to the past, has been presented and summarised here. The present review has found that while land use appears strongly implicated in erosion processes that enhance erosion, land use and climatic sediment flux signals are confounded. In conclusion, further work to improve erosion hazard assessment in the climate change context will be important in decision making to address erosion through land management. Improved monitoring and management tools will be required in optimising climate adaptation.

This literature review influenced further research using historical maps and digital spatial data from which quantification of landscape changes over time was undertaken as far as possible using a project geographic information system (GIS). The methods are found in Chapter 3 and the results are presented in Chapter 4. Together with this literature review, the research represents a major synthesis of the environmental history and contemporary erosion pressures in the catchment.

2.7 References

Aquenal Pty Ltd and Department of Environment, P, Heritage and the Arts, (2008). State of the Tamar Estuary. Hobart.

Australian Bureau of Statistics. (1910). "1301.0 - Year Book Australia, 1911." 2013, from http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/1301.01911.

Bacon, C and Banks, M (1989). "A History of Discovery, Study and Exploitation of Coal in Tasmania." Papers and Proceedings of the Royal Society of Tasmania **123**: 137-189.

Beresford, Q (2015). The Rise and Fall of Gunns Ltd. Sydney, University of New South Wales.

Bethell, LS (1980). The Story of Port Dalrymple: Life and work in Northern Tasmania. Hobart, Blubberhead Press.

BMT WBM Pty Ltd (2008). Review of Foster (1986) Report on Sedimentation Processes. Brisbane, BMT Group.

BMT WBM Pty Ltd (2010). Tamar Estuary and Esk Rivers Catchment WaterCAST Model: Final Report. Brisbane, BMT Group.

Bobbi, C, Fuller, D and Oldmeadow, D (1996). South Esk Basin State of Rivers Report. Hobart, Resource Assessment Branch, Department of Primary Industry and Fisheries.

Breen, S (2001). Contested Places: Tasmania's Northern Districts from ancient times to 1900. Hobart, Centre for Tasmanian Historical Studies, School of History and Classics, University of Tasmania.

Campbell, A (2008). Managing Australian Landscapes in a Changing Climate: A climate change primer for regional Natural Resource Management bodies. Report to the Department of Climate Change. Canberra.

Cocking, GD (1985). Agriculture. Tasmanian Year Book No 19- 1985. Hobart, Australian Bureau of Statistics.

Colhoun, EA (1984). "Estuarine Sediments at the Bowen Bridge on the Derwent River, Southeastern Tasmania." Search (Sydney) **15**(7): 224-.

Colhoun, EA, Kiernan, K, Barrows, TT and Goede, A (2010). "Advances in Quaternary studies in Tasmania." Australian Landscapes, Special Publication 346, The Geological Society of London: 165-183.

Collins, AL, Walling, DE and Leeks, GJL (1997b). "Use of the geochemical record preserved in floodplain deposits to reconstruct recent changes in river basin sediment sources." Geomorphology **19**(1): 151 - 167.

Cosgrove, R (1999). "Forty-Two Degrees South: The Archaeology of Late Pleistocene Tasmania." Journal of World Prehistory **13**(4): 357-402.

Cultural Heritage Management Australia. (2010). "Interim Report on the Jordan River Levee Excavation." 2012, from http://www.tacinc.com.au/brighton/application.htm.

Davidson, NJ, Close, DC, Battaglia, M, Churchill, K, Ottenschlaeger, M, Watson, T and Bruce, J (2007). "Eucalypt health and agricultural land management within bushland remnants in the Midlands of Tasmania, Australia." Biological Conservation **139**: 439-446.

Davies, PE, McIntosh, PD, Wapstra, M, Bunce, SEH, Cook, LSJ, French, B and Munks, SA (2005). "Changes to headwater stream morphology, habitats and riparian vegetation recorded 15 years after Forest Practices Code forest clearfelling in upland granite terrain, Tasmania, Australia." Forest Ecology and Management **217**: 331-350.

Elliot, AH and Carlson, WT (2004). "Effects of sheep grazing episodes on sediment and nutrient loss in overland flow." Australian Journal of Soil Research **42**: 213-220.

Ellis, EC (1985). "The relationships among eucalypt forest, grassland and rainforest in a highland area in north-eastern Tasmania." Australian Journal of Ecology **10**(3): 297-314.

Fensham, RJ (1989). "The Pre-European Vegetation of the Midlands, Tasmania: A Floristic and Historical Analysis of Vegetation Patterns." Journal of Biogeography **16**(1): 29-45.

Fensham, RJ and Kirkpatrick, JB (1992). "The Eucalypt Forest-Grassland/Grassy Woodland Boundary in Central Tasmania." Australian Journal of Botany **40**: 123-138.

Finucane, KJ (1935). Mathinna and Tower Hill Goldfields, Survey Bulletin No. 43. D. o. Mines. Hobart.

Fitzgerald, N and Dudley, T (2015). Plantation Restoration in Tasmania: Methodology and Prioritisation, North East Bioregional Network.

Fletcher, M-S and Thomas, I (2010a). "The origin and temporal development of an ancient cultural landscape." Journal of Biogeography **37**: 2183–2196.

Fletcher, M-S and Thomas, I (2010b). "A Holocene record of sea level, vegetation, people and fire from western Tasmania, Australia." The Holocene **20**(3): 351-361.

Flood, J (1983). Archaeology of the Dreamtime. Auckland, William Collins P.L.

Forest Practices Authority (2012). State of the Forests Tasmania 2012. Hobart, Forest Practices Authority.

Foster, DN, Nittim, R and Walker, J (1986). Tamar River Siltation Study. Manly Vale, New South Wales, The University of New South Wales Water Research Laboratory.

Gammage, B (2005). "....far more happier than we Europeans": Aborigines and farmers. London, Menzies Centre for Austraian Studies, King's College London, University of London.

Gammage, B (2011). The Biggest Estate on Earth: How Aborigines made Australia. Sydney, Allen and Unwin**:** 434.

Gilfedder, L, Kirkpatrick, J, Wapstra, A and Wapstra, H (2003). The Nature of the Midlands. Hobart, Artemis Publishing Consultants.

Goede, A (1973). "Flood Plain Stratigraphy of the Tea Tree Rivulet, Buckland, Eastern Tasmania." Australian Geographical Studies **11**(1): 28-39.

Green, G (2004). Plantation Forestry in Tasmania: The current resource, current processing and future opportunities, Timber Workers for Forests.

Grose, CJ and Moreton, RM (1996). South Esk Report: Land Capability Survey of Tasmania. Launceston, Department of Primary Industry and Fisheries, Tasmania.

Grose, MR, Barnes-Keoghan, I, Corney, SP, White, CJ, Holz, GK, Bennett, JB, Gaynor, SM and L, BN (2010). Climate Futures for Tasmania: general climate impacts, Adaptation Unit, Climate Change Office, Government of Tasmania.

Gunawardana, D and Locatelli, A (2008). Tamar Estuary Management Plan. Launceston, SFM Environmental Solutions Pty Ltd.

Hanson, R (2013, June 7-13). New fund to protect rare farm habitat. Tasmanian Country. Hobart, Davies Brothers Ltd**:** 10-11.

Haygarth, N (2011). Email communication on aspects of Tasmanian history.

Hesse, PP and McTainsh, GH (2003). "Australian dust depsoits: modern processes and the Quaternary record." Quaternary Science Reviews **22**: 2007-2035.

Hill, RS (1990). "Sixty Million Years of Change in Tasmania's Climate and Vegetation." Tasforests **2**(2): 89-98.

Hydro Tasmania (2003). South Esk - Great Lake Water Management Review: Scientific Report on Tamar Siltation.

Jackson, W (2005). The Tasmanian Environment. Vegetation of Tasmania. J. B. Reid, R. S. Hill, M. J. Brown and M. J. Hovenden. Canberra, Australian Biological Resources Study, Australian Government Department of the Environment and Heritage.

Jackson, WD (1968). "Fire, air, water and earth- an elemental ecology of Tasmania." Proceedings of Ecological Society of Australia **3**: 6-16.

Jackson, WD (1999). "The Tasmanian legacy of Man and fire." Papers and Proceedings of the Royal Society of Tasmania **133**(1): 1-14.

Jackson, WD and Brown, MJ (2005). Pattern and Process in the Vegetation. Vegetation of Tasmania. J. B. Reid, R. S. Hill, M. J. Brown and M. J. Hovenden. Canberra, Australian Biological Resources Study, Australian Government Department of the Environment and Heritage.

Jones, R (1995). "Tasmanian archaeology: Establishing the sequences." Annual Review of Anthropology **24**: 423-446.

Kershaw, P, Moss, P and Van Der Kaas, S (2003). "Causes and consequences of long-term climatic variability on the Australian continent." Freshwater Biology **48**: 1274-1283.

Kirkpatrick, J and Bridle, K (2007). People, sheep and nature conservation: The Tasmanian experience. Collingwood, CSIRO Publishing.

Kirkpatrick, JB (1991). "The Magnitude and Significance of Land Clearance in Tasmania in the 1980s." Tasforests: 11-14.

Kirkpatrick, JB (1999). A Continent Transformed: Human impact on the natural vegetation of Australia. South Melbourne, Oxford University Press.

Kirkpatrick, JB and Dickinson, KJM (1982). "Recent Destruction of Natural Vegetation in Tasmania." Search **13**(7-8): 860-861.

Lakin, R (1967). Primary Industry- Rural. Tasmanian Year Book No 1- 1967. R. Lakin. Hobart, Commonwealth Bureau of Census and Statistics, Tasmanian Office.

Lourandos, H (1968). "Dispersal of activities : the east Tasmanian aboriginal sites." Papers and Proceedings of the Royal Society of Tasmania **102**(Part II): 41-46.

Lourandos, H (1997). Continent of Hunter-Gatherers: New perspectives in Australian prehistory. Cambridge, Cambridge University Press.

MacKnight, CC (1998). Low Head to Launceston: the earliest reports of Port Dalrymple and the Tamar. Launceston, Historical Survey of Northern Tasmania.

Macphail, MK (1979). "Vegetation and Climates in Southern Tasmania since the Last Glaciation." Quaternary Research **11**: 306-341.

McIntosh, PD, Price, DM, Eberhard, R and Slee, AJ (2009). "Late Quaternary erosion events in lowland and mid-altitude Tasmania in relation to climate change and first human arrival." Quaternary Science Reviews **28**: 850-872.

McTainsh, GH (1989). "Quaternary aeolian dust processes and sediments in the Australian region." Quaternary Science Reviews **8**: 235-253.

Morgan, S (1992). Land Settlement in Early Tasmania: creating an antipodean England. Cambridge, University of Cambridge.

Moss, PT, Thomas, I and Macphail, M (2007). "Late Holocene vegetation and environments of the Mersey Valley, Tasmania." Australian Journal of Botany **55**: 74-82.

Newitt, L (1988). Convicts and Carriageways: Tasmania's Road Development until 1880 Hobart, Department of Main Roads.

Norris, RH, Lake, PS and Swain, R (1980). "Ecological Effects of Mine Effluents on the South Esk River, North-eastern Tasmania. I. Study Area and Basic Water Characteristics." Australian Journal of Marine and Freshwater Research **31**: 817-827.

Norris, RH, Swain, R and Lake, PS (1981). "Ecological Effects of Mine Effluents on the South Esk River, North-eastern Tasmania. II. Trace Metals." Australian Journal of Marine and Freshwater Research **32**: 165-173.

Oliver, RL, Hart, BT, Olley, J, Grace, M, Rees, C and Caitcheon, G (1999). The Darling River: Algal Growth and the Cycling and Sources of Nutrients. Murray-Darling Basin Commission Project M386, CRC for Freshwater Ecology; CSIRO Land and Water.

Paton, R. (2010). "Fact sheet: Addendum to Interim Report on the Jordan River Levee Excavation." Brighton Bypass Reports and Submissions: Cultural Heritage Management Australia, 2012, from http://www.tacinc.com.au/brighton/application.htm.

Pike-Tay, A, Cosgrove, R and Garvey, J (2008). Systematic seasonal land use by late Pleistocene Tasmanian Aborigines **35**: 2532-2544.

Pirzl, H and Coughanowr, C (1997). State of the Tamar Estuary: A review of environmental quality data to 1997. Supervising Scientist Report 128. Canberra, Environment Australia, Commonwealth Department of Environment, Sport and Territories.

Preston, K (2011). "Mount Victoria Goldfield, Tasmania: a case of unfulfilled potential?" Journal of Australasian Mining History **9**: 183-198.

Pretyman, ER. (1950-70). "Index to Tasmanian Place Names." Retrieved 30 January 2010, from http://www.statelibrary.tas.gov.au/__data/assets/pdf_file/0012/239799/Sap-Spr.pdf.

Prowse, TAA and Brook, BW (2011). "Climate change, Variability and Conservation impacts in Australia." Pacific Conservation Biology **17**: 168-178.

Prowse, TAA and Brook, BW (2011). "Climate change, Variability and Conservation impacts in Australia." Pacific Conservation Biology **17**: 168-178.

Ryan, L (1996). The Aboriginal Tasmanians. St Leonards, Allen and Unwin.

Selby, MJ (1993). Hillslope Materials and Processes. New York, Oxford University Press.

Sigleo, WR and Colhoun, EA (1982). "Terrestrial dunes, Man and the late Quaternary environment in southern Tasmania." Palaeogeography, Palaeoclimatology, Palaeoecology **39**: 87-121.

Syvitski, JPM and Kettner, A (2011). "Sediment flux and the Anthropcene." Philosophical transactions of the Royal Society **369**: 957-975.

Tamar Estuary and Esk Rivers Program (2015). Tamar Estuary and Esk Rivers Catchments Water Quality Improvement Plan. T. NRM North. Launceston, NRM North.

Tasmanian Land Conservancy. (2013). "Protected Areas on Private Land program." 2013, from http://www.tasland.org.au/majorprogrammes/papl.

Thomas, I (1993). "Late Pleistocene environments and Aboriginal settlement patterns in Tasmania." Australian Archaeology **36**: 1-11.

Thompson, D. (2009). "Plantations 2020: Plantations and Managed Investment Schemes Facts." 2013, from http://www.plantations2020.com.au/.

Turney, CSM, Flannery, TF, Roberts, RG, Reid, C, Fifield, LK, Higham, TFG, Jacobs, Z, Kemp, N, Colhoun, EA, Kalin, RM and Ogle, N (2008). "Late-surviving megafauna in Tasmania, Australia, implicate human involvement in their extinction." Proceedings of the National Academy of Sciences **105**(34): 12150 – 12153.

Twelvetrees, WH (1907). The Mangana Goldfield, Geological Survey Bulletin No. 1. D. o. Mines. Hobart.

Walker, JB (1897). "Some notes on the tribal divisions of the aborigines of Tasmania." Papers & Proceedings of the Royal Society of Tasmania: 176-187.

White, CJ, Grose, MR, Corney, SP, Bennett, JB, Holz, GK, Sanabria, LA, McInnes, KL, Cechet, RP, Gaynor, SM and Bindoff, NL (2010). Climate Futures for Tasmania: Extreme Events Technical Report. Hobart, The Antarctic Climate & Ecosystems Cooperative Research Centre

Williams, RJ, Bradstock, RA, Cary, GJ, Enright, NJ, Gill, AM, Liedloff, AC, Lucas, C, Whelan, RJ, Andersen, AN, Bowman, DMJS, Clarke, PJ, Cook, GD, Hennessy, KJ and York, A (2009). Interactions between climate change, fire regimes and biodiversity in Australia - a preliminary assessment. Canberra, Report to the Department of Climate Change and Department of the Environment, Water, Heritage and the Arts.

Chapter 3

Methods and materials

The fundamental objective of the experimental component of the present study was to obtain distinctive elemental “fingerprints” for four broad soil types in the pilot study catchment. It would test the viability of using existing geological mapping as an alternative fundamental unit in suspended sediment modeling in the Tamar basin. It was also intended to use the soils data generated for the pilot study area together with LIDAR data for application in improvement of the resolution and certainty of erosion hazard mapping at sub-catchment scale (pers. comm., Darren Kidd, DPIPWE, 2016).

It has been recognised in review of the literature and from catchment considerations (its setting and size; limited road access) that random stratification (probability sampling) and the ideal collection of large soil sample sets comprehensively representative of climatic (temporal) cycles and environmental (spatial) variability would be costly in time, analytical reagents and laboratory resources. As a compromise, a representative soil sampling strategy was devised by a systematic desktop scrutiny of detailed geographical mapping with an objective to obtain data representative of the soil types. It was an opportunity to develop a refined methodology; to develop efficient soil discrimination techniques of practical value in improving soil mapping.

3.1 Desktop techniques

3.1.1 Geographic information system

A geographic information system (GIS) was used for quantitative spatial analyses of the Tamar basin, its catchments and the upper catchment pilot study area as well as for cartography and data presentation. Spatial metadata including reliability are detailed in Appendix 1.

Spatial data were collated and analysed on a Dell *E5400 Latitude* computer using ESRI *ArcGIS 9.3* to *10.4.1* software. All data for analysis and mapping in the present project used consistent projection and datum, i.e. GDA94 (Geocentric Datum of Australia 1994), Map Grid of Australia (MGA) Zone 55. Where original projections of datasets differed they were calibrated and reprojected for use in the GIS. Paper maps used were digitised and projected appropriately for analysis.

GIS datasets were defined in digital layers, including Tasmanian river catchments, surface geology at 1:25,000 and 1:500,000 scales, erosion hazard, land systems, contemporary vegetation, land use (2002 & 2013), rivers, sub-catchments, towns and other identified locations and the road network. The catchments of the Tamar estuary (Figure 1.3) were clipped from the Tasmania-wide data, while the pilot study area, consisting of the upper South Esk sub-catchment and Break O'Day catchment, was clipped from the South Esk catchment for analysis.

The clipped spatial data were analysed for areal extent and distribution of geological units at both 1:25,000 and 1:500,000 scales, as were the land use, land systems, vegetation data and erosion hazard. All of these data were examined across the Tamar Basin and in greater detail in the pilot study area in preparation for soil sampling.

The erosion hazard digital data (as used in *WaterCAST* modeling) were compiled from *Soil and Landscape Grid of Australia* data (CSIRO, 2016) into six value range classes using *K*LS* i.e. K: soil erodibility (based on soil properties of carbon, topsoil permeability and structure) and LS: slope length and slope steepness factors (pers.

comms., A. Baldwin, NRM North, August 2016; D. Kidd, DPIPWE, September 2016). Essentially, *KLS* is a component of the algorithm A=RKLSCP for the *Revised Universal Soil Loss Equation* (RUSLE) (Institute of Water Research, 2002). Other RUSLE components are R: rainfall runoff erosivity factor, C: cover management factor and P: support practice factor.

The detailed road network data were used in planning, including evaluation of vehicular access. Cartography produced from the GIS was used both during fieldwork and for presentation throughout this thesis.

3.1.2 Examination of geological mapping

The Tamar basin's geological diversity and known differentials in vulnerability to erosion between granite based and other soil types inspired the present project (Grant *et al.*, 1995; Laffan *et al.*, 1998; Laffan *et al.*, 2003; Davies *et al.*, 2005; Forest Practices Board, 2005). Using the project GIS and current digital geological data, maps of the surface geology were produced for each catchment in the Tamar Basin (data origin mapped at 1:500,000 scale) and for the pilot study area (data mapped at 1:500,000 and 1:25,000 scale) (Mineral Resources Tasmania, Undated). A key to geological symbols is found in Appendix 2.

The cartography developed from digital *geological* mapping is shown here as a component of the project methodology, rather than part of the "results" of this study. Using the project GIS, maps of the surface geology were produced for each catchment in the Tamar Basin (Figures 3.1 to 3.6).

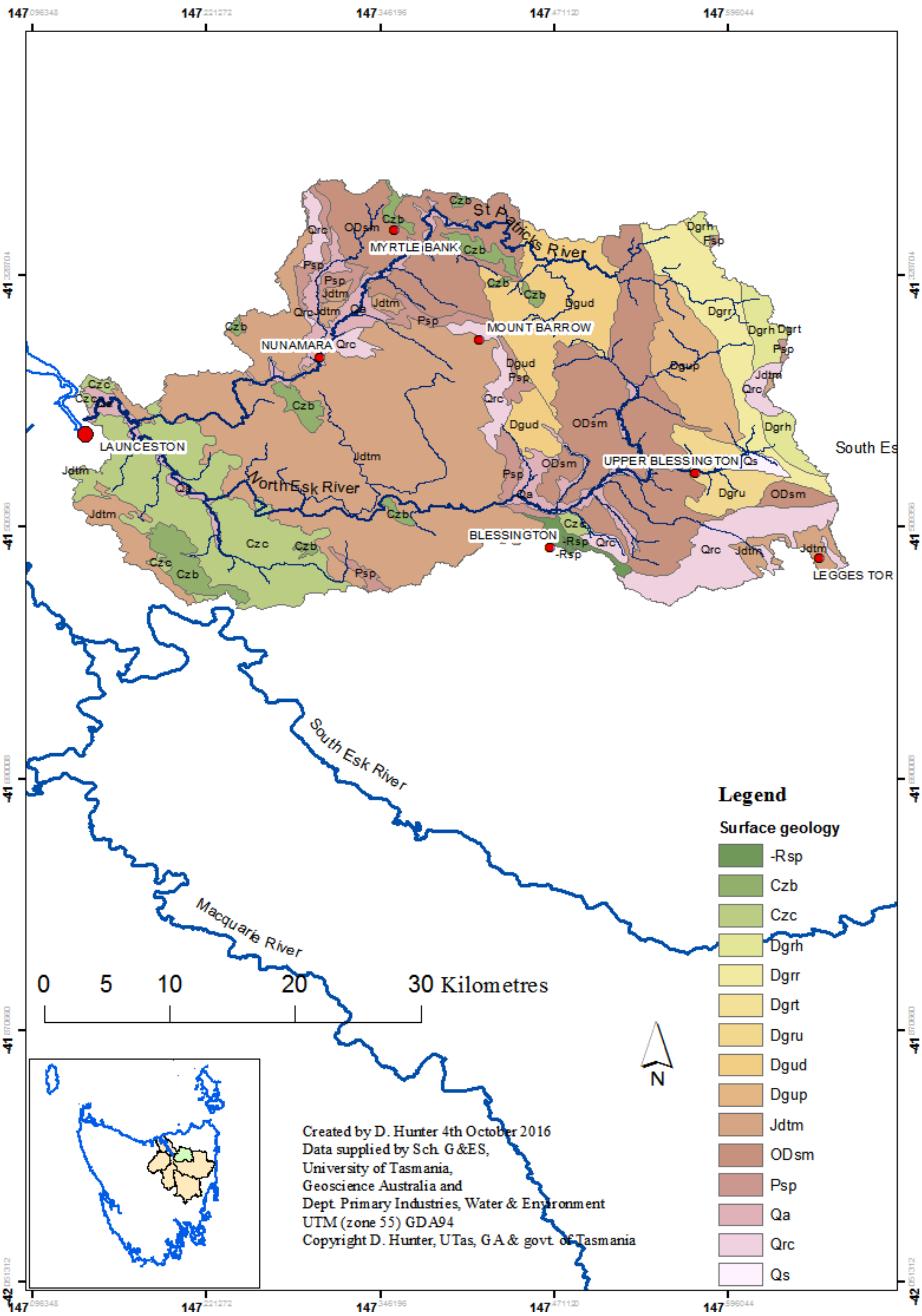


Figure 3.1: Surface geology of the North Esk catchment (1:500,000 scale mapping).

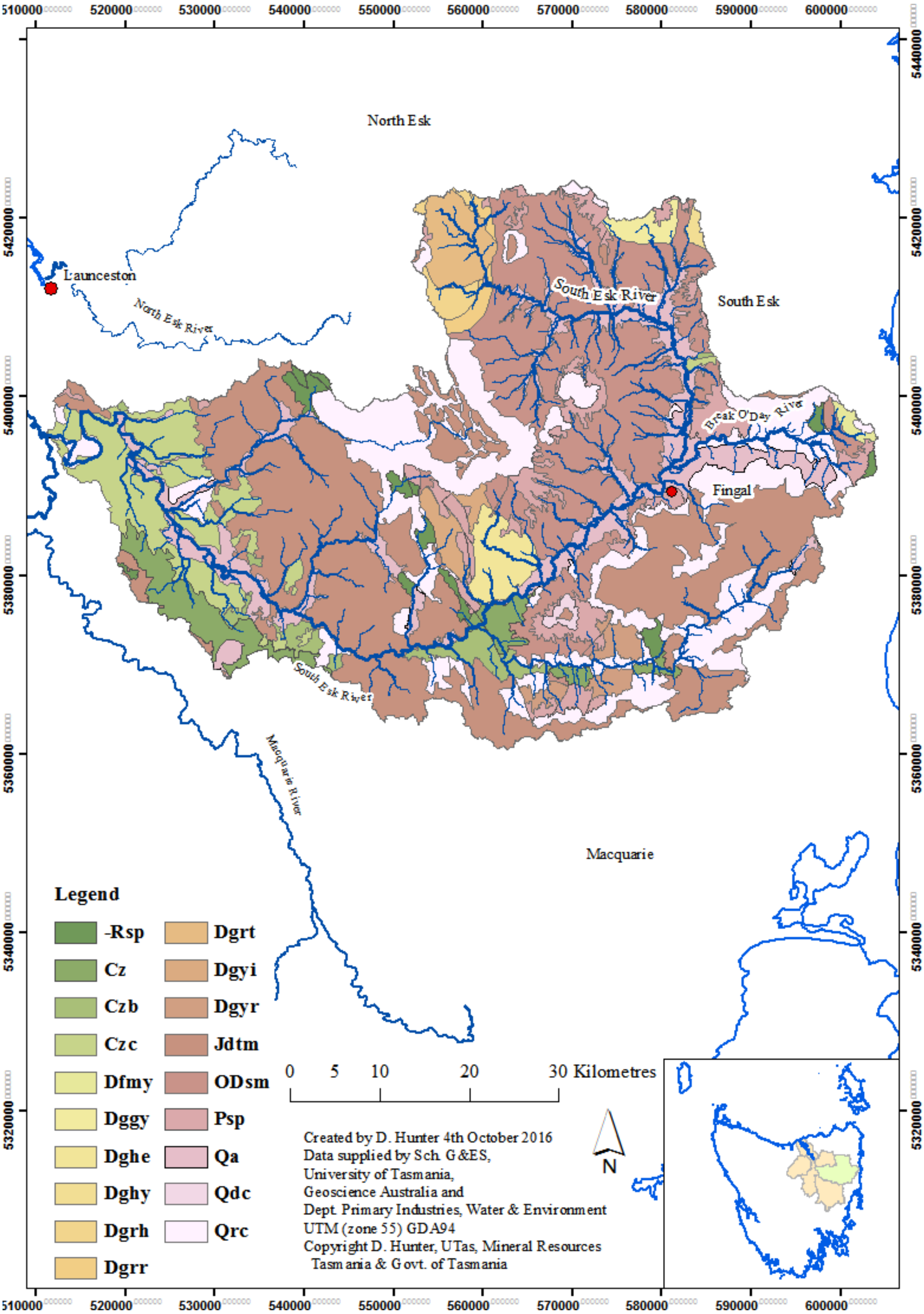


Figure 3.2: Surface geology of the South Esk catchment (1:500,000 scale mapping).

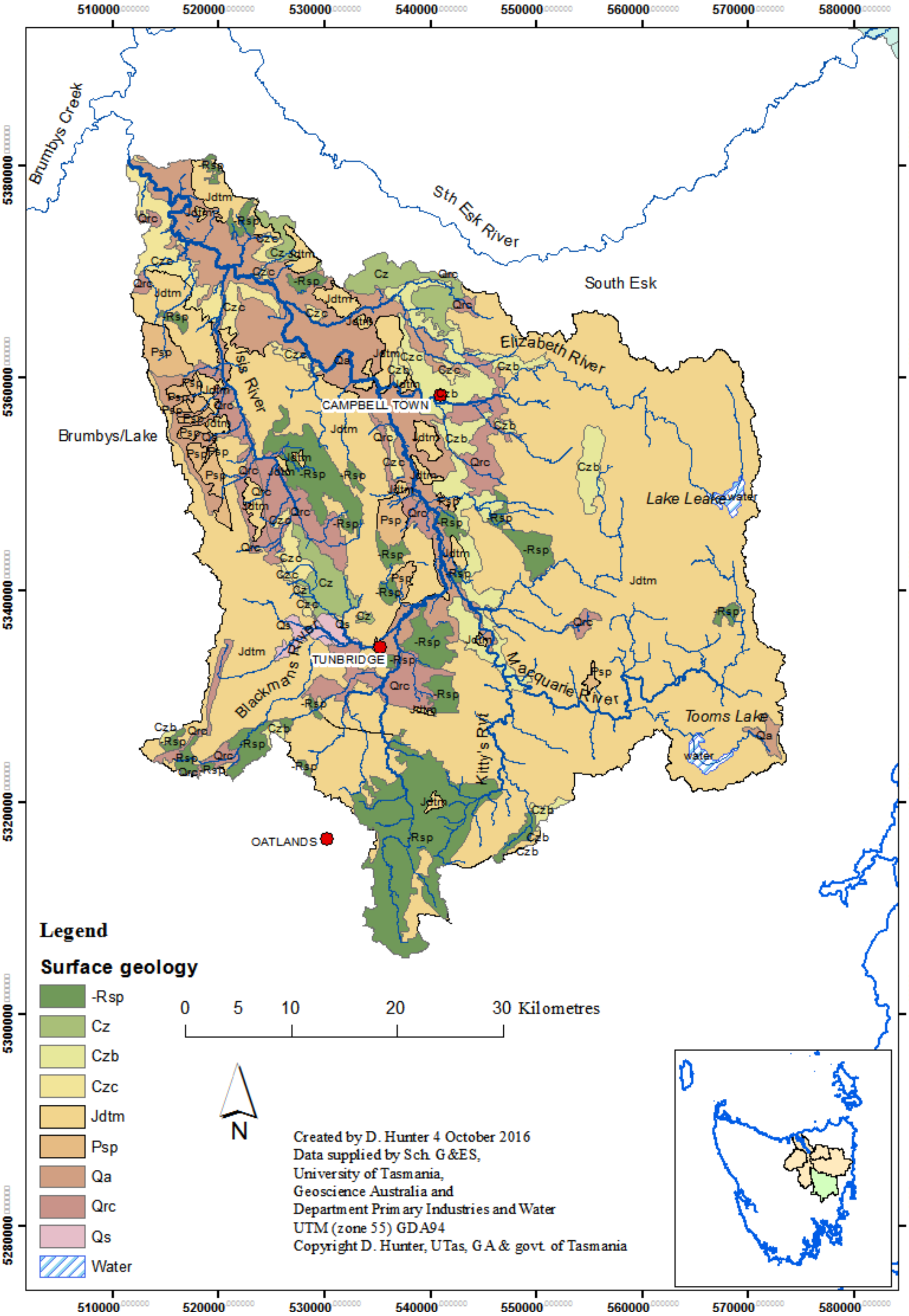


Figure 3.3: Surface geology of the Macquarie catchment (1:500,000 scale mapping).

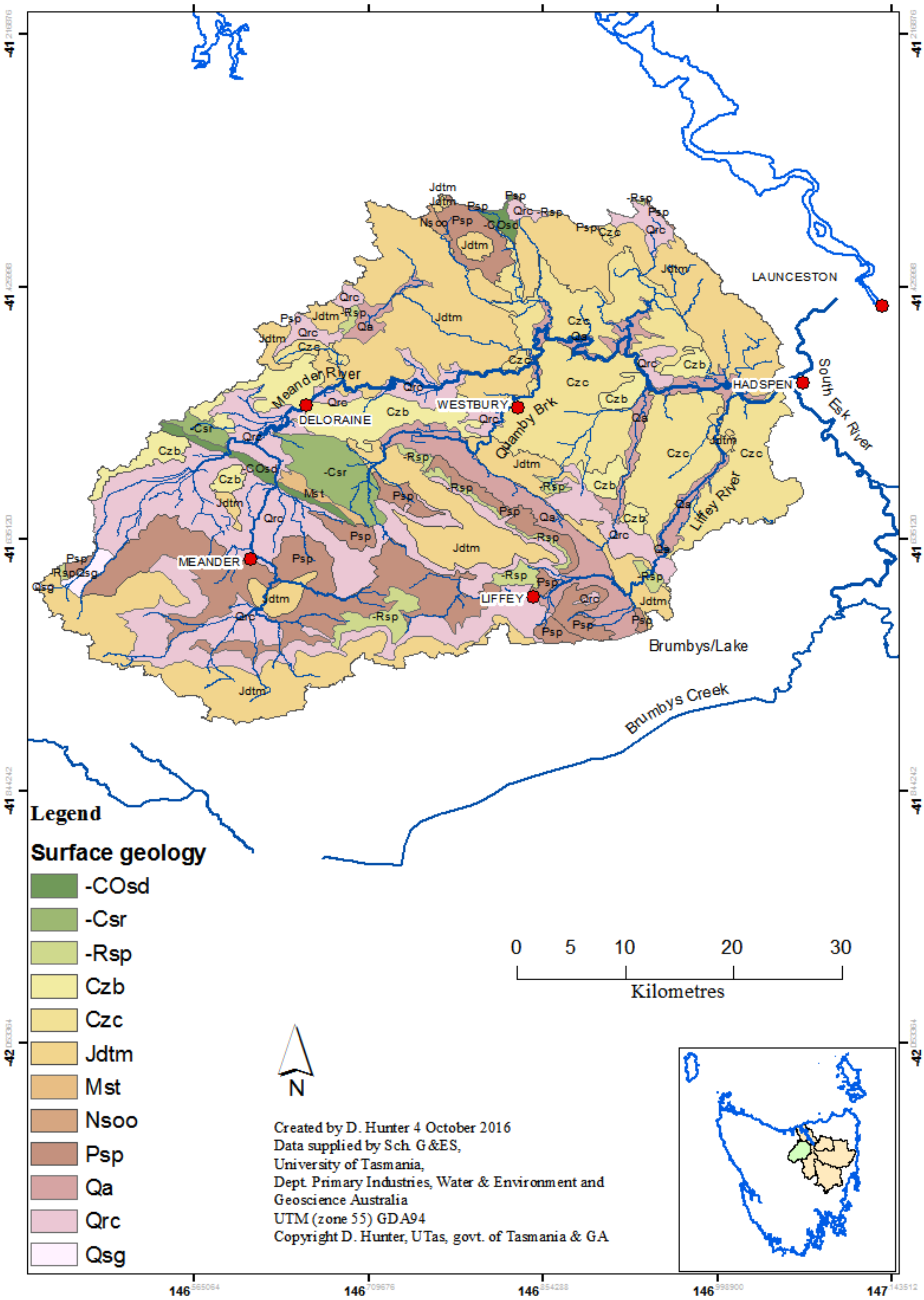


Figure 3.4: Surface geology of the Meander catchment (1:500,000 scale mapping).

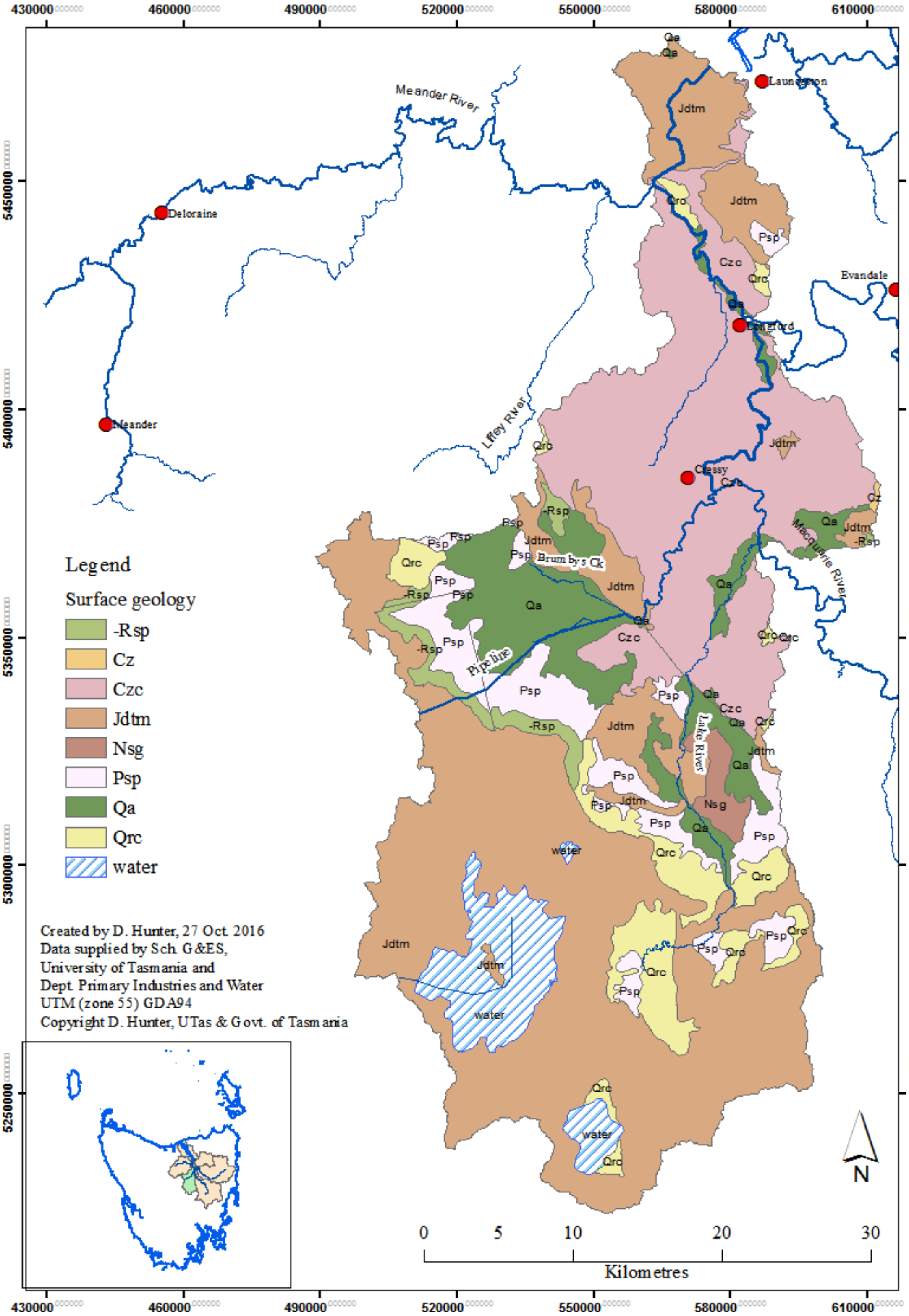


Figure 3.5: Surface geology of the Brumbys/Lake catchment (1:500,000 scale mapping).

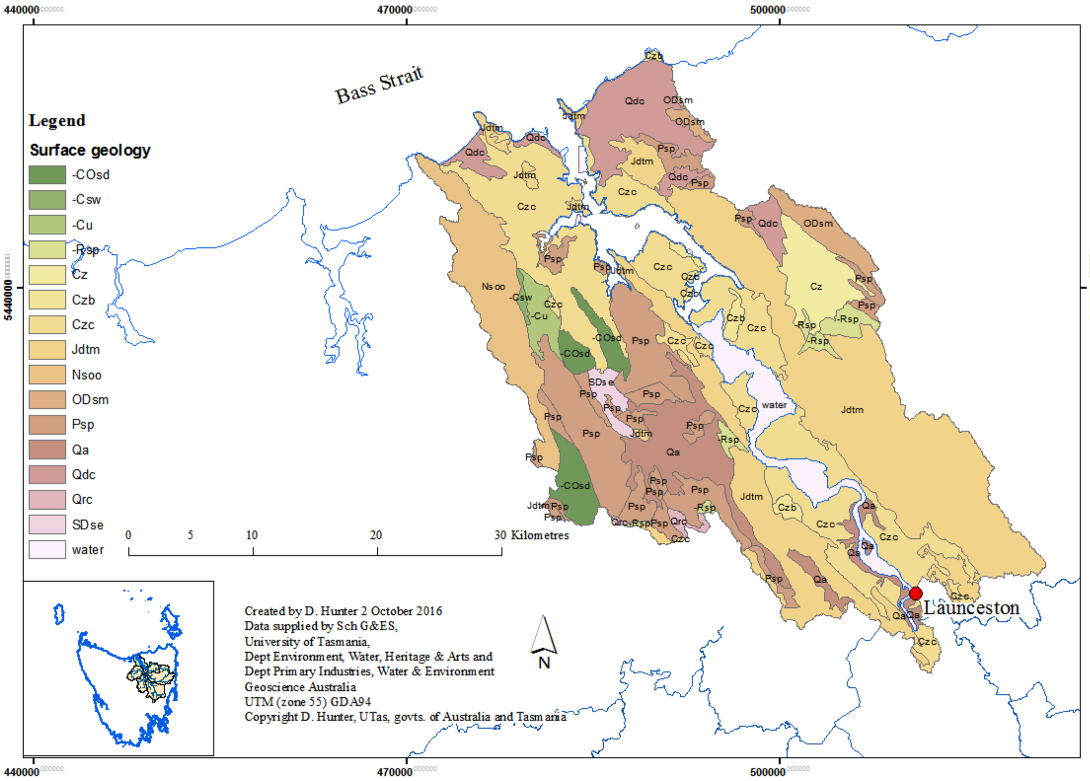


Figure 3.6: Surface geology of the Tamar catchment (1:500,000 scale mapping).

The geological mapping in the pilot study catchment was then examined in greater detail for soil classification.

3.1.3 Soil classification in the study setting

The surface geology of the pilot study catchment (1:500,000 scale mapping) is shown in Figure 3.7. The 1:25,000 scale geological mapping considered in sample stratification was considered too complex to present in cartography in this thesis.

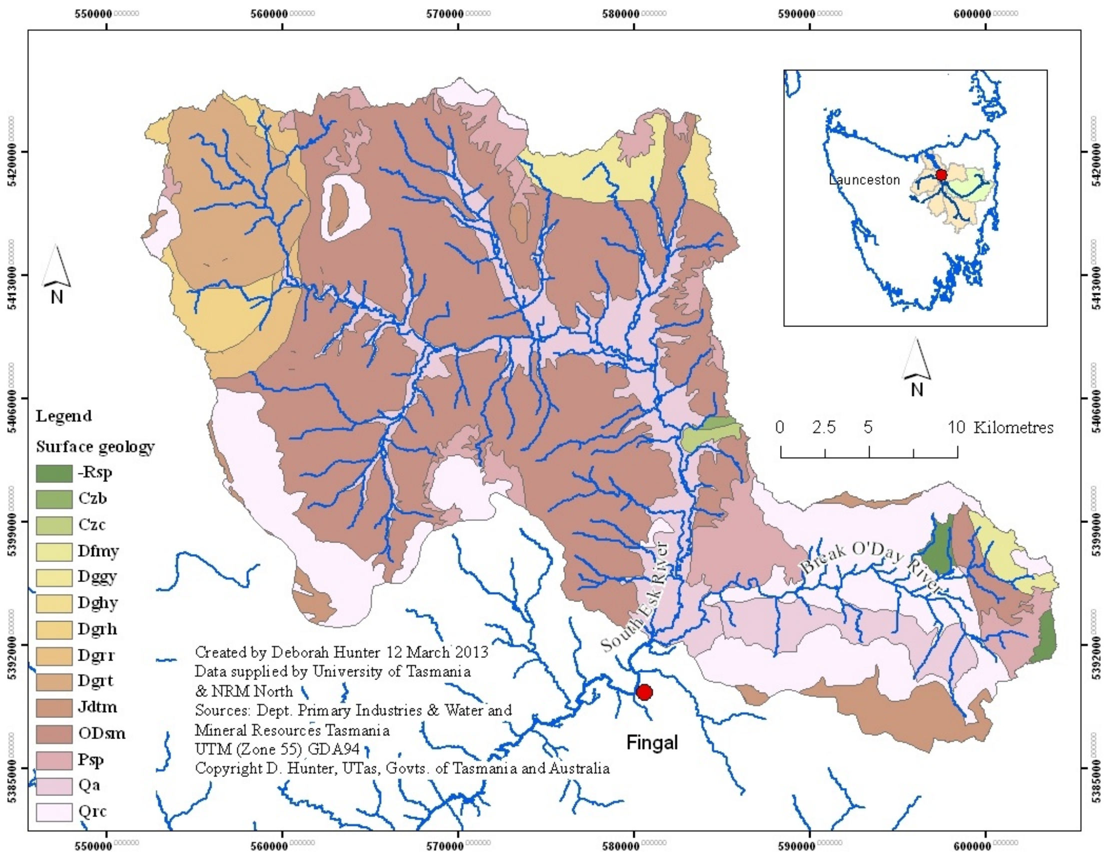


Figure 3.7: Upper South Esk study catchment (including Break O'Day), northeast Tasmania, showing surface geology (1:500,000 scale mapping).

Key to rock types (key to geological codes, Appendix 2):
Basic igneous rocks: Czb, Jdtm and Qrc
Acid igneous rocks: Dfmy, Dggy, Dghy, Dgrh, Dgrr and Dgrt
Sedimentary rocks: -Rsp, Czc, ODsm and Psp
Quaternary sediments: Qa and Qrc.

The assessment of feasibility of soil type as a potential fundamental landscape unit for sediment flux and erosion hazard modeling was dependent on the accuracy of the available data (geological or parent material mapping), confirmed by appropriate sampling and analysis of soils. However, the complexity of the geology evident from examination of the data dictated the need for simplification or classification of the soil types as well as appropriate stratification prior to sampling. The literature on suspended sediment source fingerprinting methodology was informative on geological classification, soil characterisation and sampling stratification as well as digestion techniques for elemental analyses of soils (for example Melaku *et al*., 2005; Walling, 2005; Davis & Fox, 2009; Poleto *et al.,* 2009; Collins *et al*., 2012).

Australian studies, for example Olley and Caitcheon (2000), have indicated that soils in Australian landscapes can be biogeochemically distinctive. Olley and Caitcheon (2000) classified soils of the catchment into broad geological types i.e. basic igneous, acid igneous and sedimentary. Using only elemental properties, soils of sedimentary rock parent materials can even be differentiated from the Quaternary sediments formed by their erosion and transport elsewhere (Roy *et al*., 2010; Hagedorn *et al*., 2011). Elemental properties have been used exclusively with success for example in Collins *et al*. (2012) and also in marine sediments, for example Bowie *et al.* (2010). However, critically, heavy reliance on elemental soil properties demands careful representation of the soils in sampling stratification (Dale *et al*., 2008).

Sampling stratification and choice of sampling sites in the present study were based on evaluation of the surface geology of the pilot study catchment that confirmed four potential types of soil classifications, namely basic (mafic) igneous parent material, acid (felsic) igneous, sedimentary rocks and a fourth geological type, the Quaternary sediments (mainly alluvium and some colluvium) derived from the erosion products of the three topographically superior types of materials (Figure 3.7). This classification provided the framework for representative soil sampling with the aim of identifying chemical properties comprising a geochemical “fingerprint” that statistically discriminated the soil types.

The four broad types of rock found in the study catchment were comprised of 14 geological units at the 1:500,000 scale (Figure 3.7). It was found that eight principal 1:500,000 scale units within the four rock types accounted for 970 km^2 (95%) of the study catchment. Accordingly, these eight units were regarded as representative of the surface geology and miscellaneous units accounting for only 5% of the catchment area were ignored. The more detailed 1:25,000 scale geological mapping was then queried for principal 1:25,000 scale component units within the selected 1:500,000 scale units. It was found the four broad types of rock found in the study catchment were comprised of 70 units at the 1:25,000 scale, of which 15 accounted for 856 km^2 (84%) of the study catchment and were accordingly selected as providing appropriate representation of the four geological types. The representation of potential suspended sediment sources by both mapping scales and the extent of the geological units selected is given in Table 3.1 below. A guide to geological unit codes is given in Appendix 2.

Table 3.1: Geological classification of the soils of the study catchment and the extent of representative units.

Source (% catchment)	Classification rock type	Area[a] (km^2)	1:500,000 scale unit	Area[b] (km^2)	1:25,000 scale unit	Area[b] (km^2)
Soil type 1 (19%)	Basic/mafic igneous	192	Jdtm (Tasmanian dolerite)	35	Jd	34
			Qrc (predominantly dolerite-derived colluvium)	155	Qptd	131
Soil type 2 (14%)	Acid/felsic igneous	140	Dgrt (Tombstone Creek granite)	63	Dgaap	44
					Dgae	19
			Dgrh (Hogarth Road granite)	22	Dgnv	13
					Dgnx	8
			Dgrr (Russells Road granite)	18	Dgne	18
Soil type 3 (50%)	Sedimentary rocks	513	ODsm (Mathinna supergroup sediments)	434	ODqp	122
					ODq	218
					ODqm	28
			Psp (Lower Parmeener supergroup sediments)	69	Plb	11
					Pfs	23
					Pus	13
Soil type 4 (17%)	Quaternary sediments[c]	172	Qa (stream alluvium & older alluvium of river terraces)	148	Qha	40
					Qpao	111
			Qrc (stream colluvium/ alluvium)	24	Qha	24
Area (km^2)	Total	1016	Total	970	Total	856

[a]Total area of rock type in the catchment
[b]Area of selected representative units in the catchment
[c]Quaternary colluvium unit (1:500,000 scale unit Qrc) occurs both as highland colluvium fans (dominantly dolerite boulders, 1:25,000 scale unit Qptd) and as lowland colluvium mapped as geologically recent fluvial deposits (1:25,000 scale unit Qha).

Small areal discrepancies exist between the two scales of geological datasets in mapped water bodies and in the exclusion of the minor geological units discounted for sampling. There are also minor inconsistencies within datasets (according to the custodians of the digital data) for reasons such as unresolved edge matching issues encountered during digitisation of maps. Other discrepancies have occurred because of differences in mapping resolution of the two scales, reflected in accuracy of polygon boundaries and some minor variations in assignment of geological units by the creators of the digital datasets.

3.1.4 Sampling stratification

Appropriate sampling stratification and sample replication across the range of physiographic settings and within each of the four soil types was particularly fundamental to discriminating the soils using only elemental properties. From the literature, the number of sample locations required for sufficient or appropriate representation within each soil classification has varied according to anticipated spatial and temporal heterogeneity and remains unresolved. There is often compromise according to practical constraints (Davis & Fox, 2009).

Details of sampling density were found lacking in many studies, as was the use of probabilistic sampling strategies. Ideal sampling density was experimentally derived by Pengfei and Walling (2017) who collected 52 samples over 8 transects across a small (7 ha) cultivated field. Soil distribution variability alone was calculated as 17% based on ^{137}Cs concentrations, assuming caesium fallout distribution to be uniform. It was suggested 25-100 samples would be required for 95% confidence in some elemental property values, given geological variability. In sampling stratification for acid digestion and analysis of elemental properties, Collins *et al*. (2012) took 15-20 samples in each of four potential sediment source classifications in each of seven sub-catchments of a 35 km long river (area not stated). The density representation of potential sediment sources in the present study approximates that in Carter *et al*. (2003), where 150 samples were taken in a 1,932 km^2 catchment of four geological zones.

In the pilot study catchment, soil sample sites were distributed considering both the areal extent of the eight selected 1:500,000 scale geological units comprising the four classifications and the relative areal extents of the upper South Esk sub-catchment and Break O'Day catchment. The density of sampling within each soil classification was principally guided by classification complexity, as judged by the number of principal 1:25,000 scale component geological units (Table 3.2; Figure 3.8). Within this strategy, locations that were logistically permissive of field access were targeted, with the final location of accessible sample sites also guided by obstacles to access that were encountered and observations in the field.

Table 3.2: Sampling stratification of soils by geological type.

Soil type (% catchment)	Sample sites (n)	Area[a] (km^2)	1:500,000 scale unit	Sample sites (n)	Area[b] (km^2)	1:25,000 scale unit	Sample sites (n)	Area[b] (km^2)
Soil type 1 (19%)	9[c]	192	Jdtm	3	35	Jd	3	34
			Qrc	6	155	Qptd	6	131
Soil type 2 (14%)	10	140	Dgrt	4	63	Dgaap	3	44
						Dgae	1	19
			Dgrh	3	22	Dgnv	2	13
						Dgnx	1	8
			Dgrr	3	18	Dgne	3	18
Soil type 3 (50%)	20	513	ODsm	14	434	ODqp	5	122
						ODq	5	218
						ODqm	4	28
			Psp	6	69	Plb	4	11
						Pfs	1	23
						Pus	1	13
Soil type 4 (17%)	15	172	Qa	12	148	Qpao	6	111
						Qha	6	40
			Qrc	3	24	Qha	3	24
Total	54	1016			970			856

[a]Total area of geological type in the catchment
[b]Area of selected representative units in the catchment
[c]Soil type 1 was allocated 10 sample sites, one of which was not sampled.

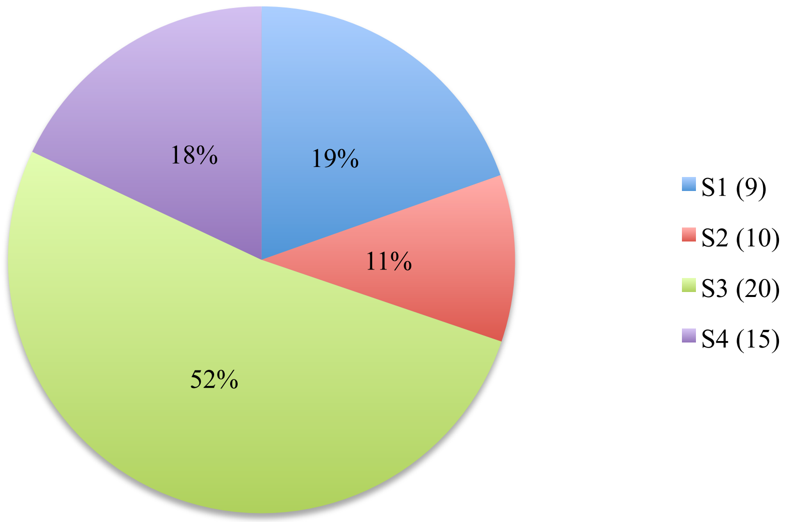


Figure 3.8: Soil types as percentage of the study catchment area (number of sample sites). Soil type 1 was allocated 10 sample sites, one of which was not sampled.

Targeting of actively eroding sites e.g. that were well connected to the drainage network was impractical in the study setting, given the size of the catchment, a paucity of available resources and remoteness of drainage lines to the road network. There was a lack of previous studies and comprehensive recent aerial photography at high resolution. However, the selection of sample site locations after the above geological criteria were fine-tuned using the detailed attributes of Tasmanian vegetation and land systems data (data sources and caviats, Appendix 1), to ensure the inclusion of a range of vegetation (land use), topographic and climatic settings. By virtue of six-digit codes, land systems data integrate 1. climate (rainfall), 2. geological age of surface materials, 3. type of surface rock (two igneous and two sedimentary types in the study catchment), 4. altitude and 5. landforms. Sometimes a sixth unique identifier number is included, generally for differences in soils and vegetation when the first five digits of land systems codes are the same (refer to individual sample site land systems, Appendix 3; land system codes, Appendix 4).

Therefore, the number of sample sites allocated per geological or soil classification varied with this heterogeneity. For example, while 20 sites were allocated to represent soil type 3 (50% of the study catchment area), 15 sites were disproportionately allocated to represent soil type 4 (17% of the study catchment). The altitudinal and geographic distribution of 20 sample sites across the catchment mid-slopes was considered representative of soil type 3. However, while the component 1:25,000 scale geological units of soil type 4 comprised one contiguous extent of the fluvial reaches of the study area (Figure 3.7), this extent varied widely in climate, had a complex upstream vegetation mosaic and potential for geochemical variation along its reach according to variation in the proportion of materials eroded from the other three sources. Hence sampling density was increased relative to area in soil type 4 compared to soil type 3 to account for the expected variation in geochemical characteristics (Figure 3.8). Strategically, soil type 1 was allocated 10 sample sites, however one was not sampled due to inaccessibility.

Of the total 55 sites selected for soil sampling, 40 were in the upper South Esk (78% of the study area) and 15 in the Break O'Day catchment (22% of the study area). Each sample site was assigned a numerical identity corresponding to the soil type (1, 2, 3 or 4), followed by a period and a unique site number (Figure 3.9). For example, Site 16 in soil type 3 was designated as S3.16.

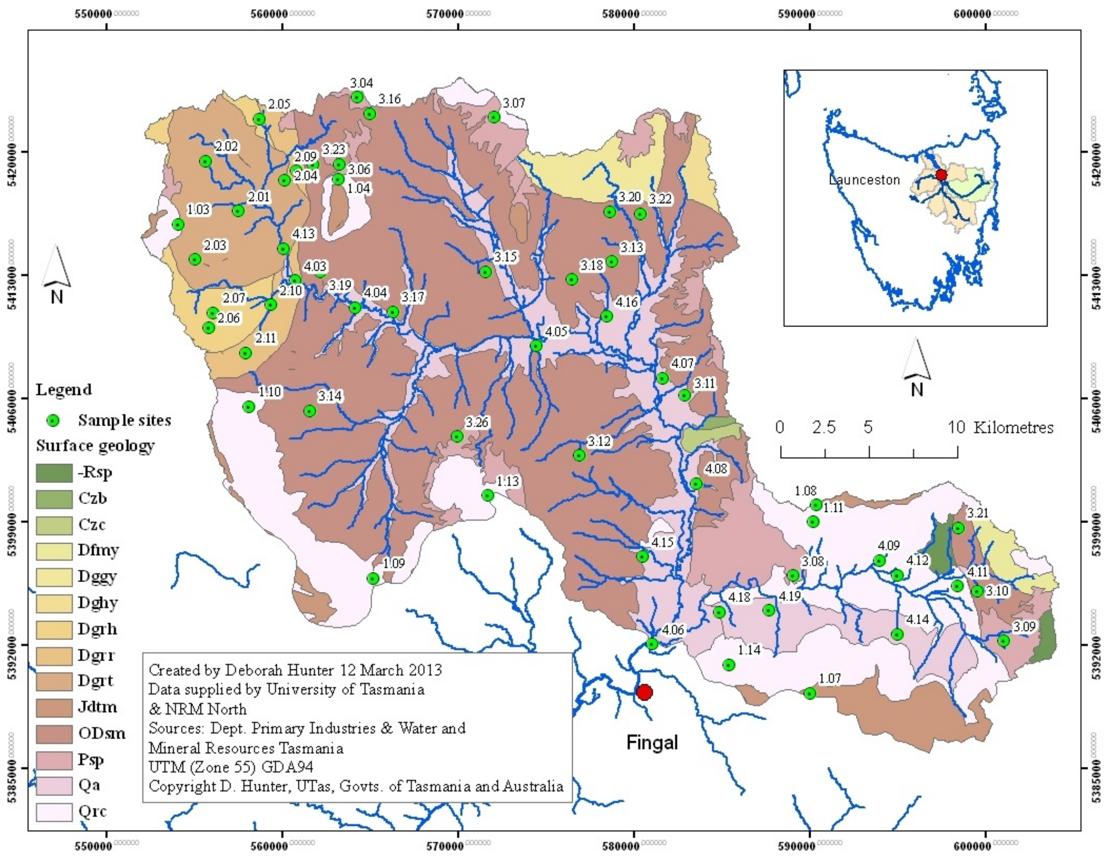


Figure 3.9: Upper South Esk study catchment (including Break O'Day) showing surface geology (1:500,000 scale mapping) and sample sites

3.2 Field techniques

3.2.1 Soil sampling

The spatial co-ordinates of each selected sample site and maps from the project GIS were used in the field during sampling trips. A Garmin *GPSmap 76CSx* global positioning system (GPS) handset was used to confirm selected sample site locations and record actual sampling site coordinates and altitude accurately in the field (estimated positional error 2.3 to 7.9 m). Soil sampling was conducted over 15 days during November 2010 to November 2011, with sample sites selected using the project

GIS. A total of 54 of the intended 55 sites were sampled, some a second time due to insufficient yield of the required <63 μm fraction in the original samples.

The land use data were too generalised for use in sampling stratification. In particular, the data did not differentiate forestry regeneration stages nor provide up to date plantation coverage data within the production forestry area, which as a land use type was prevalent over much of the study setting prior to and during the course of this project. Therefore, cartography from the project GIS guided *ad hoc* sample site reselection in the field if and as required in case of the need to re-stratify on the basis of representing land use across the sampling.

Where sample sites were found to be inaccessible, sample sites were relocated on an *ad hoc* basis within the same geological unit, to nearby locations if possible. If a selected sample site was found to be located within a recently harvested forestry area, the site was relocated, where possible, to an undisturbed internal remnant stand of native vegetation or at the margin of the cleared area in an adjoining stand of trees, to ensure an intact soil profile for sampling. In the case of substantial relocation, a new identification code was allocated to the revised sample site. The target surface geology and vegetation communities of relocated sites were validated *post hoc* on the GIS, using GPS co-ordinates of actual sites sampled. Samples were rejected if the location and/or soil characteristics were inconsistent with the target unit.

It was apparent from the literature that sampling both sub- and topsoil is essential in characterising soils. Sampling sub-soil is particularly important. Across a breadth of Australian and American studies, it has been found that subsoil erosivity is four to ten times that of surface soil (Oliver *et al.*, 1999). Subsoil erosion includes rill, piping, tunnel, gully and stream bank erosion (Davis & Fox, 2009). Various researchers have sampled subsoil directly from the sidewalls of eroding stream banks, gullies or rills (Collins *et al.*, 1998; Carter *et al.*, 2003; Krause *et al.*, 2003; Walling, 2005). In these studies, subsoil was easily accessed and excavation was not required, whereas composite subsoil samples may also be scraped from the walls of excavated soil profiles, from the base of the topsoil to the regolith (extent or depth of subsoil) to characterise subsoil or account for its erosion (Soil Survey Division staff, in Davis & Fox, 2009).

In the present study, at each single location, several sub-samples of topsoil were homogenised into one, after Davis and Fox (2009). The appropriate depth of topsoil was estimated from field observations (from 1-5 cm). Composite topsoil samples for each site were comprised of 6-10 scrapes of 0-2 cm depth, randomly located within a 10 m radius of the dug soil profile, excluding any horizon O (leaf-litter or grass sod). Composite subsoil samples were comprised of a scrape from the base of horizon A (topsoil) to the base of horizon B, as defined by the start of horizon C (decomposing regolith) where possible (Figure 3.10; Appendix 3). At some sites, horizon C was not encountered. In the case of deep, friable soils, at least 0.5 m depth was excavated for subsoil sampling and for hard, compacted or stony ground difficult to dig by hand, it was attempted to attain a depth of at least 0.5 m.

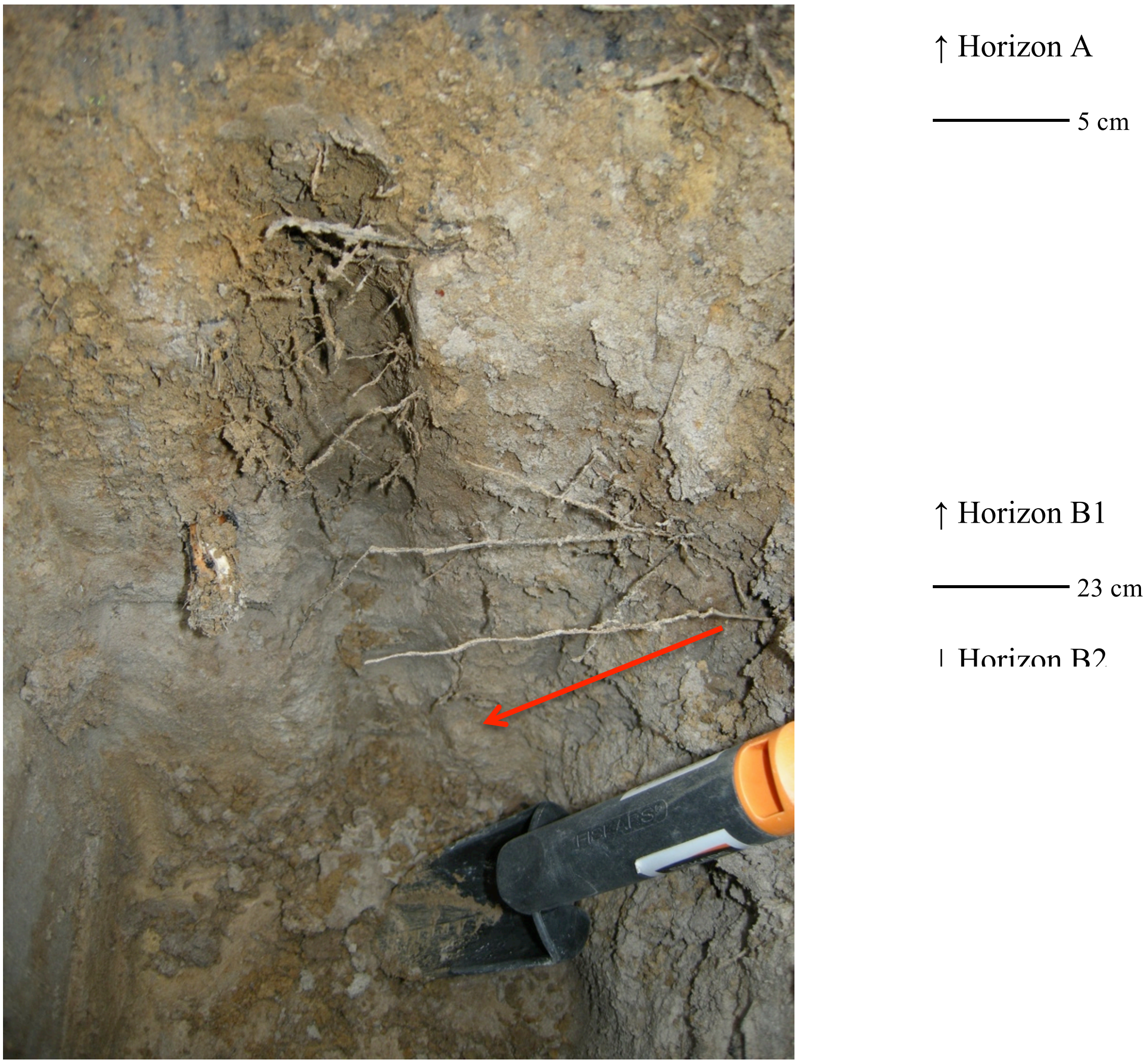


Figure 3.10: Composite scrape from base of A horizon to regolith, representing subsoil sample. The 5-37 cm depth of the subsoil scrape extends to the B horizon-regolith boundary indicated by the arrow. This profile was exposed to a final soil profile depth of 44 cm (site 3.26, Appendix 3).

Sampling techniques using plastic trowels were adapted after Collins *et al*. (1997a; 2010), except that soil profiles were exposed by metal spade for most subsoil samples. At two sites, exposed soil profiles at road cuttings were sampled for subsoil following removal of the aerially weathered layer. Trowels and spade were cleaned using native water (where available) or rainwater and nylon brush, followed by a deionized water rinse to avoid contamination of samples between sites.

Press-seal zip-lock bags were filled to capacity (up to approximately 1 kg field weight) for each sample, double bagged to avoid cross-contamination, labeled with the site code and soil depth and stored in a chiller box for transport to the laboratory the same day. At the laboratory, samples were stored in the chiller box and processed for analysis as soon as possible.

3.2.2 Field data collection and site confirmation

The site descriptions and physical characteristics of the soil profiles and soils were recorded in the field for *post hoc* confirmations, including comparing soils for consistency within soil types (5.1; Appendix 3).

The complete field data included site code, date(s) sampled, elevation, GPS record number, elevation, estimated positional error, location co-ordinates (easting, northing), site description (vegetation and land use), detailed soil profile description (horizons/structure, depth, colour and texture) and slope position. These data were collated with GIS data including geological codes (1:25,000 and 1:500,000 scales), as well as details of sub-catchment, land system and mapped vegetation community. These data can be found in Appendix 3 and a key to land systems in Appendix 4. The exposed soil profile (e.g. Figure 3.10) and setting (e.g. Figure 3.11 below) were photographed at each sample site.

Following soil sampling, the data were examined for verification of sample site target characteristics. The sample distribution across the study catchment and within geological soil types was verified with respect to the field data, including target geology, altitude and distribution across four simplified land use categories (native vegetation, native vegetation regeneration, plantation and agricultural/exotic). The distinction “native vegetation” or “native vegetation regeneration” was attributed according to actual field observations at each site (site descriptions, Appendix 3). *Native vegetation* indicates recognisable *TasVeg* mapped vegetation communities, including those thinned at some time in the past by either low-impact selective forestry activities or natural processes such as fire. However, *native vegetation regeneration* is attributed to a spectrum of recovery stages where sites lack a recognisable vegetation community structure, following contemporary forest harvesting. *Native vegetation regeneration* may also have been applied if natural processes such as fire or mass movement had substantially transformed community structure, however no such sites were found. An example of thinned native vegetation is illustrated in Figure 3.11 below, while Figures 3.12 and 3.13 bracket a spectrum of native vegetation regeneration.

Figure 3.11: Example of native vegetation designation (dry *Eucalyptus amygdalina* coastal forest and woodland, S2.10) thinned by forestry and/or fire. Sites of relatively low intensity disturbance are regarded as "native vegetation."

Figure 3.12: Example of native vegetation regeneration designation (mapped as wet *Eucalyptus obliqua* forest with broadleaf shrubs, S3.20). Community structure has not yet recovered following harvest.

Figure 3.13: Example of a native forest regeneration site that had just been harvested (mapped as dry *Eucalyptus delegatensis* forest and woodland, S3.16). Because of recent mechanical soil disturbance in the logging coup, the samples were taken to the side of the clearing within the remnant copse in the foreground.

3.3 Laboratory techniques

To test the approach taken in distinguishing soil types for potential suspended sediment modeling and to allow for future potential for direct sediment tracing, it was intended the data generated in the present study be consistent in quality with that expected in (bio)geochemical fingerprinting work. Normal practice is to work with the <63 μm fraction of soil samples that is transportable as the suspended fraction of fluvial sediment when eroded (Walling, 2005; Fu *et al.*, 2008; Davis & Fox, 2009). However, more recently, some studies have advocated that the use of the <10 μm fraction better matches the suspended fraction, as discussed in Collins *et al.* (2017).

3.3.1 Weight loss on ignition (LOI) methods

Weight loss on sequential ignition for estimation of organic matter and carbonate content was conducted for all source topsoils and subsoils (N=108).

LOI analyses of 2 ±0.10000 g of the <63 μm fraction of all source samples were undertaken in a Prochem Labware *Modutemp* muffle furnace following oven-drying overnight at 105^{o}C. Heating times and temperatures were adapted from Wang *et al*. (2011). A temperature of 490^{o}C for 14 h was used for organic matter assay while 800^{o}C for 14 h was used for inorganic LOI.

LOI reproducibility was assessed within and between batches across the range of soils. Within batches precision was tested using triplicate samples (five topsoils and 3 subsoils) while controlling furnace position (front, centre and back). Between-batches reproducibility was determined for seven topsoils and six subsoils. Furnace position was random.

3.3.2 Sample pre-treatment

Since small particles travel primarily as part of larger composite particles or flocs in most fluvial systems (Phillips *et al.*, 2000; Davis & Fox, 2009), disaggregation is performed, normally following oven drying and before sieving to assist recovery of the small size fraction.

Soil samples were processed as soon as practicable on return from the field. Soils were air-dried on labeled plastic plates at 19.0-22.5^{o}C under a suspended cloth cover to minimise air-borne contamination. Samples were gently disaggregated using a glazed ceramic pestle in a plastic bowl in a fume hood. Samples were transferred with a camelhair brush (to avoid retention of sample fines in the bowl due to static charge), onto a 2 mm nylon mesh to screen out gravel and coarse organic matter. The <2 mm portion of each sample was sieved using a Westernex *Flexistack* polystyrene sieve assembly fitted with 63 µm nylon mesh in an Endcott *Test* mechanical sieve shaker for 25 minutes and the <63 µm fraction transferred to clean, labeled Sarstedt jars using a camelhair (anti-static) brush. Working environments were cleaned between samples and all equipment coming into contact with soil was washed with hot soapy water, rinsed with de-ionised water and oven dried at 105^{o}C before re-use. The brush was cleaned between samples using paper towels.

The samples (as collected) air-dried to a mean bulk weight of 463.9 g (N=108), of which the mean obtained fine fraction (<63 µm) was 23.6 g (5.1%), ranging from 0.6-105.7 g (0.1-10.1%). Repeat sampling of several lower yielding samples was necessary to obtain sufficient <63 µm fines for analyses. Substantial masses of soil samples would be required to extract sufficient of the <10 µm fraction dominating the suspended sediment entering the Tamar estuary and as discussed in Collins *et al.* (2017).

3.3.3 Sample digestion

Inductively coupled plasma mass spectrometry (ICP-MS) was readily available for multi-elemental analysis of the soils. Acid digestion methods suitable for ICP-MS processing were researched with available resources in mind, as well as advantages and disadvantages, and are summarised in Table 3.3.

Table 3.3: Review of selected soil sample digestion methods for ICP-MS analysis. Where blank, information was not provided.

Reference	Heating equipment	Sample size	Sample attack; acid volume, temperature, duration	Pre-analysis treatment/ comments
Viers *et al*. (2008)			HNO_3 & HF (36 h at 80°C); HCl (36 h at 80°C); HCl & HNO_3 (36 h at 100°C)	
Petherick *et al*. (2009) (after Marx *et al*., 2005)	Open beakers on a hotplate	0.08 g	Dilute HNO_3; HF (100°C overnight, keeping moist with 6 N HNO_3)	Diluted samples x 2000, centrifuged, and "an aliquot" added to a standard solution, acidified with HNO_3 and centrifuged again
Collins *et al*. (2010a; 2010b)			Treatment with aqua regia (3:1 HCl/HNO_3), followed by drying of the filtrate and ignition	For analysis of samples high in iron oxides (after Allen, 1989)
Allen (1989)	Lidded crucibles	0.1 g	HF (7 mL) & $HClO_4$ (1 mL) (2 h "slow digest"), evaporate until fumes are seen, add H_2SO_4 (1 mL) and evaporate to drive off $HClO_4$	For breaking down silicates and organic matter in soils; pre-treatment with $HClO_4$ and HNO_3 is recommended if the soil is high in organic matter.
			Alkaline fusions	For complete dissolution of silicates
			Acid fusions	For dissolution of resistant minerals
Marx and Kamber (2010)	Screw-top beakers		HF and HNO_3 (10:1)	(after Eggins *et al.,* 1997)
Eggins *et al*. (1997)	Screw-top beakers		HF and HNO_3 (10:1); evaporated, refluxed in 6 N HNO_3, again evaporated then dissolved in 2 mL of concentrated HNO_3	Beakers were ultrasonicated several times during digestion to disaggregate granular material and render it more susceptible to acid attack. Digests were diluted x 1000-1250.
	Microwave or "bomb" digestions			Used to ensure complete dissolution of resistant phases such as zircon.
Marx *et al*. (2010), after Eggins *et al.* (1997)			Addition of HCl to destroy residual organic matter after HF and HNO_3 digestion	Total dissolution was not aimed for or required for the trace elements of interest. Process modified according to Kamber *et al.* (2003) and Kamber (2009)
Nehyba *et al*. (2010)			Lithium borate/metaborate mixture melt followed by dissolution in HNO_3	For determination of main oxides by ICP-OES
	Open vessels	1 g	A mixture of HF and $HClO_4$ (Method ISO 14869-1)	For determination of total heavy metals by ICP-MS
Morelli *et al*. (2012)	Screw top Teflon beakers on a hotplate		HNO_3 and HF, HNO_3, HCl and HNO_3	For determination of trace elements by ICP-MS and major elements by ICP-OES.

Of particular interest, granite-derived materials (found in the pilot study area) have been widely recognised as difficult to digest (for example Taylor *et al.,* 2002). Bowie *et al*. (2010) regarded poor recovery of Ti as indicative of incomplete dissolution of refractory minerals, while Yu *et al.* (2000) gauged dissolution success by recovery of the high field strength elements (HFSE) group from standard reference materials (SRMs). Some workers have centrifuged digests prior to analysis (for example Petherick *et al.,* 2009), presumably to check for incomplete dissolution or the formation of precipitates.

There can be important practical considerations in the dilution of digested samples for ICP-MS analysis, best expressed by Eggins *et al*. (1997). The dilution factor used is a compromise between sufficient sample size to allow for environmental sample heterogeneity, amount of sample available, availability of large volumes of clean reagents, required detection limits and analyte suppression effects which can be severe where total dissolved solid contents exceed 0.2%.

After consideration of the literature, it was decided to adapt a mixed acid digestion for analysis using ICP-MS. A mixed acid (HNO_3-HF-HCl) hotblock acid digestion method was adapted after Yu *et al*. (2001) and Viers *et al.* (2008), with ca. 0.25 g of sample heated at 110^{o}C for 48 hrs in 6 mL HNO_3, 2 mL HCl and 2 mL HF in *Savillex*® Teflon (PFA) 60 mL (25.9 x 168.7 mm) vials using an A.i. Scientific *Aim 500* block digestor.

Concentrated instrument quality/high grade acids were used for digestion: Seastar Instrument Quality (IQ) HNO_3 70%; Merck *Suprapur*® HCl 30% (digestions 1 to 3); Seastar IQ HCl 35% (digestion 4); Seastar *Baseline*® HF 48%. Ultra high quality

(UHQ) water ($\geq$18 MΩ cm^{-1}) from a Barnstead *Nanopure* ultrafiltration unit was used for dilution of all digest solutions.

All labware used for digestion and for preparation and transport of solutions for analysis was prepared using hot soapy wash, triple rinsed in deionised water, soaked in 10% v/v nitric acid bath (generally >48 h), triple rinsed in UHQ water and oven dried before use. Between each use, the digestion vials were washed in hot soapy water, rinsed and heated with lids loosened for 2 h @ 90^{o}C with 2 mL AR grade HCl and repeated using 2 mL AR grade HNO_3 before decanting and soaking in the acid bath.

Each digestion and analysis batch was comprised of soil samples as well as triplicates of blanks and SRM(s). SRMs chosen as analogues for the soil types were BHVO-2 basalt (soil type 1), AC-E granite (soil type 2) and NIST2711a Montana soil (soil types 3 and 4), from which analytical reproducibility could be assessed from element recovery and precision. A range of sampled soils were digested and analysed in triplicate to assess sample homogeneity and reproducibility, one was triplicated twice. Prior to sub-sampling for digestion, soil samples and reference materials were oven dried at 105^{o}C overnight or longer and cooled in desiccators.

Digestions were undertaken in a fume hood equipped with an alkaline scrubber. After transferring 0.2500 ± 0.0125 g soil and SRM samples to the digestion vials, acid was added, the vials were ultrasonicated (Unisonics type *FX8*) for 30 s, and left overnight in the block digestor at room temperature, allowing fumes to escape. Following this initial step, the vial lids were tightened to within ¼ turn of being fully tightened, and the digestions further ultrasonicated for 2 minutes with agitation then slowly brought to

110^{o}C, held for 16 h then cooled. This process was repeated twice (total heating time of 48 h) with the digestions ultrasonicated for 2 minutes prior to each heating stage.

Following digestion, condensate was rinsed from the lids into the vials using UHQ water and the digests were evaporated to dryness at 85^{o}C and cooled. The residue was twice taken up with 2 mL HNO_3 and evaporated to dryness to remove any remaining HF. Solutions were prepared for analysis by first heating the residue to 35^{o}C with 2 mL HNO_3 then ultrasonicating the vials for 30 s. The digests were transferred into prepared 120 mL Sarstedt jars using 3 rinses of UHQ water. The digests were diluted to about 100 ± 1.000 g using UHQ water. Analysis was generally conducted within 1-2 days of digestion.

Samples were processed and analysed over four batches.

3.3.4 ICP-MS analysis and data preparation

Sector field ICP-MS instrumental analyses were conducted by Dr Ashley Townsend at the Central Science Laboratory, University of Tasmania. Instrumental specifications are provided below (Table 3.4).

Table 3.4: ICP-MS instrumental specifications.

Component	Specifications
Instrument	ELEMENT 2 High resolution ICP-MS (Thermo Fisher, Bremen, Germany)
Available resolutions (m/Δm)	400 (low), 4000 (medium) and 10,000 (high)
Torch	Fassel type (Thermo Fisher, Bremen, Germany)
Spray chamber	20 ml Cyclonic (Glass Expansion, Melbourne, Australia)
Nebuliser	0.2 mL/min Micromist (Glass Expansion, Melbourne, Australia)
Cones	Standard Ni cones (sampler and skimmer with 1.0 and 0.75 mm diameter orifices)
Autosampler	ASX-500 (Cetac, Omaha, USA)

Prepared sample digests were analysed following further gravimetric dilution of 50x to a final dilution of approximately 20,000x, with prior overnight settling to allow complete separation of any residues. This larger dilution factor than normally encountered in ICP-MS geochemical assays (for example Yu *et al.*, 2000) allowed the determination of both major and many trace elements using the same sample preparation. All samples were spiked with indium (as an internal standard), with nitric acid (final concentration 1%) also added prior to analysis. Quantification was by means of external calibration with fresh blanks and calibration standards prepared daily. Standard samples were regularly analysed as unknowns to provide a measure of instrument drift through the course of each analytical sequence. A 5% nitric acid rinse was conducted for 150 s between each standard/sample. Data acquisition was preceded by 120 s uptake. Two separate instrument scan methods were used to cover the majority of elements, noted as “other” and “REE” method in the ICP-MS operating and method parameters (Table 3.5).

Table 3.5: ICP-MS instrument operating and acquisition parameters.

Parameter	"Other" method	"REE" method
Guard electrode	Deactivated	Deactivated
RF power	1350	1350
Cool gas flow (L/min)	~15 [a]	~15 [a]
Auxilary gas flow (L/min)	~0.7 [a]	~0.7 [a]
Sample gas flow	~0.95 [a]	~1.03 [a]
Torch position	a	a
Scan type	Magnetic jump with E-Scan across small mass range	Magnetic jump with E-Scan across small mass range
Number of scans	Low resolution: 3 runs, 4 passes; Medium resolution: 4 runs, 5 passes	Low resolution: 3 runs, 10 passes
Isotopes selected[b]	Low resolution: ^{85}Rb, ^{88}Sr, ^{89}Y, ^{90}Zr, ^{93}Nb, ^{95}Mo, ^{111}Cd, ^{115}In [c], ^{118}Sn, ^{121}Sb, ^{133}Cs, ^{137}Ba, ^{178}Hf, ^{181}Ta, ^{182}W, ^{205}Tl, ^{208}Pb, ^{209}Bi, ^{232}Th, ^{238}U Medium resolution: ^{27}Al, ^{28}Si, ^{31}P, ^{32}S, ^{45}Sc, ^{47}Ti, ^{51}V, ^{52}Cr, ^{55}Mn, ^{56}Fe, ^{59}Co, ^{60}Ni, ^{63}Cu, ^{66}Zn, ^{115}In [c]	Low resolution only: ^{115}In [c], ^{137}Ba, ^{139}La, ^{140}Ce, ^{141}Pr, ^{146}Nd, ^{149}Sm, ^{153}Eu, ^{160}Gd, ^{159}Tb, ^{163}Dy, ^{165}Ho, ^{167}Er, ^{169}Tm, ^{173}Yb, ^{175}Lu
Comment on oxide minimisation strategies, and typical oxide formation rates (%)		Instrument tuning optimised with minimum oxide formation as a prerequisite. NdO/Nd: ~0.4%

[a]Adjusted daily for maximum signal intensity and stability
[b]Where alternate isotopes were monitored, only those selected for use in working datasets are shown
[c]As internal standard

Analytical data for 47 elements were supplied on a sample equivalent basis (mg element per kg soil dry wt.) expressed as mg/kg, following concentration corrections for analytical (instrument) blanks and any spectral interferences. Barium was assayed using both scan methods during each sample run providing another measure of QA across both methods. Barium concentrations were found to be in good agreement, varying by less than 7% for 106 of the 108 samples (two samples varied by 11% and 12%).

Sample-equivalent element concentrations attributed to acids (calculated from the manufacturers' certificates of analysis) were negligible. For most elements, concentrations were <0.0005 mg/kg, while Al, Cr and Fe were <0.003 mg/kg and Zn was 0.001 <mg/kg.

Blank data (mg/kg) were calculated on a *sample equivalent* basis from [element$_{\text{blank solution}}$] (µg/kg)*50 (analytical dilution)*dilution factor/1000, where dilution factor = wt. of prepared solution/sample equivalent wt. Blank data are given in Appendix 5.

For most elements, the analytical (instrument) detection limit (ADL; 3 x SD [element$_{\text{blank solution}}$]) on a *sample equivalent* basis from analytical (instrument) blanks was <1.50 mg/kg, while ADL was for Al and Mo: 19.1 mg/kg; Nd: 7.52 mg/kg; Fe, Zn and Bi: ≤3.13 mg/kg.

For most elements, the method detection limit (MDL; 3 x SD [element$_{\text{blank solution}}$]) on a *sample equivalent* basis from digestion process blanks was <1.50 mg/kg, while MDL was for Al: 30.2 mg/kg; Fe: 7.91 mg/kg; Cu, Zn and Mo: ≤2.70 mg/kg.

For most elements, the limits of quantitation (LOQ; 10 x SD [element$_{\text{blank solution}}$]) on a *sample equivalent* basis from digestion process blanks was ≤2.50 mg/kg, while LOQ was for Al: 101 mg/kg; Fe: 26.4 mg/kg; Cu, Co and Mo <9.00 mg/kg.

Values for LOQ calculated from process blanks results are shown in Table 3.6. A number of elements, namely P, S, W and Ta, were poorly detected and were not considered for the SRMs and soil samples working datasets, nor was Ni due to variable background levels attributable to the instrument's nickel cones.

Table 3.6: Limits of quantitation calculated from process blanks for the elements considered in this study (LOQ=10 x SD [element $_{\text{blank solution}}$]).

Element	LOQ (mg/kg)	Element	LOQ (mg/kg)
Al	101	La	0.125
Sc	0.278	Ce	0.301
Ti	4.89	Pr	0.638
V	0.799	Nd	0.557
Cr	1.40	Sm	0.116
Mn	1.68	Eu	0.0706
Fe	26.4	Gd	0.101
Co	1.47	Tb	0.0822
Cu	8.83	Dy	0.111
Zn	8.04	Ho	0.0744
Rb	1.23	Er	0.0843
Sr	2.29	Tm	0.0747
Y	0.119	Yb	0.113
Zr	0.233	Lu	0.0548
Nb	2.03	Hf	0.100
Mo	7.08	Tl	0.149
Cd	0.280	Pb	0.800
Sn	1.07	Bi	0.657
Sb	0.252	Th	0.0180
Cs	0.349	U	0.0176
Ba	2.44		

3.4 Statistical techniques

Statistical analyses were performed on Mac OSX (Version 10.5.8 to 10.9.5), using the software Microsoft® *Excel® for Mac 2011* (Version 14.1.4) with Addinsoft™ *XLSTAT* (Version 2012.5.01; Copyright Addinsoft 1995-2012). Statistical testing of the power of each element to distinguish the soils was first undertaken to eliminate redundant elemental properties from the dataset. The optimal multivariate identity that discriminates the soils can then be selected (Collins & Walling, 2002; Walling, 2005). Non-parametric statistics are routinely applied, since the assumptions of parametric statistics cannot be met, including that the typically small datasets in such studies do not tend to follow normal distributions (confirmed by normality tests) and that there are no population parameters, since each dataset is merely a collective sample of the soil (Daniel, 1978).

Data were processed for statistical identification and verification of the multiple soil type fingerprint as described below after Collins *et al.* (2012).

The Kruskal-Wallis H-test, the distribution-free non-parametric equivalent of the analysis of variance, was used to test each element as a potential fingerprint property. The test is for contrasts between values from different soil categories. Its power efficiency of ~95.5% makes it particularly useful for the relatively small sample sets collected in sediment fingerprinting study catchments. If the critical value is exceeded by inter-category differences, Ho is rejected, and the tracer is retained as a potential fingerprint property.

Discriminant (function) analysis (DA; DFA) was used to test those potential properties passing the Kruskal-Wallis H-test for their ability to classify all the soil samples from the study catchment into the correct categories, and into surface- and sub-soil (if specified). This is a test of the discriminatory power of individual properties.

Finally, for identifying a fingerprint that distinguishes multiple soils, a multi-variate stepwise selection algorithm based on the minimisation of Wilk's lambda was used to identify the optimal combination (and least necessary number) of properties from those properties selected in the previous analysis. Individual properties are combined sequentially to reduce the Wilk's lambda value. A property is rejected when outperformed by another. A lambda value of 1 occurs when all soil category means are equal, while a desirable value of close to zero indicates inter-category variability exceeds within-category variability.

This methodology was developed for quantitative application in multiple soil type study settings, as is the present pilot study setting.

Rowan *et al*. (2000) and Collins and Walling (2002) advised the use of the smallest possible number of individual properties in soil identity discrimination in order to avoid over-parameterisation problems in the subsequent (un)mixing models, providing that the number of properties exceeds the number of soil classifications in order to maximise dimensionality in the analysis. Should the stepwise DFA fingerprint selection algorithm identify too few properties, more should be added (Collins & Walling, 2002). While the use of multiple tracers presents an overdetermined mass balance matrix, the advanced statistical techniques required for such solutions are easily resolved in desktop computing (Davis & Fox, 2009).

Overdetermination, as discussed by Rowan *et al*. (2000) and Davis and Fox (2009), exists where $m \geq n$ (where m is the number of tracer properties and n is the number of distinct soil groups). These workers examined uncertainty in source ascription modeling and the two optimisation procedures available to assign the relative contributions of each soil group where $m \geq n$. Uncertainties could be constrained in the frequentist ("least-squares") approach of error minimisation, but a Bayesian integration approach via Monte Carlo (Markov Chain Monte Carlo; MCMC) was argued to be superior in further reducing these uncertainties. Bayesian statistics using MCMC sampling were seen to offer improved management of the problems that arise from natural variability in soil properties, as used in the present study.

Specifically, each potential fingerprint property was tested for significant differences between soil types to eliminate redundant elemental properties. The *Kruskal-Wallis* test (*alpha*=0.05), using *Monte-Carlo* simulations and multiple pairwise comparisons of the *Steel-Dwass-Critchlow-Fligner* procedure (two-tailed test), were then conducted on the combined soils fingerprint working dataset of 33 elements. The tests compared observations per soil type for each of the potential fingerprint properties, the hypothesis being that at least one of the possible pairs between soil sample sets are not from the same population. Where a significant difference between soils for a property was found but the particular pair/s could not be specified by the *Steel-Dwass-Critchlow-Fligner* procedure, *Mann-Whitney* pairwise two-tailed tests were conducted for all combinations of the soils datasets to confirm the significant difference(s).

Operational parameters for *Discriminant Analysis* (fingerprint selection analyses) are given in Table 3.7 below. Any conflicting terminology evident between statistical language in common use generally and that used in the *XLSTAT* Manual and *Discriminant Analysis* dialogue box is explained. The data spreadsheet format consisted of a row of variables measured for each sample, with each column representing a potential fingerprint property. No weightings were applied to the data. *XLSTAT* default *factor axes* offered for charting display during computations were accepted, other visualisations explored manually later to confirm soil type compliance. Considering soil “fingerprinting” studies across the literature, the soil datasets were among the small range.

Table 3.7: Operational parameters used in running *XLSTAT Discriminant Analysis.* Source: *XLSTAT 2011* Manual © 2011, Addinsoft: http://www.addinsoft.com.

Tab	Required data	Options/setting used	Explanation
General	X/Explanatory	Quantitative or Qualitative variables	Select all the columns of potential fingerprint property variables for the samples
	Y/Dependent	Qualitative	The dependent variables or predictor variables are the soil types; a column created to identify the *a priori* classification (S1, S2…) for each sample is selected
Options	Tolerance	Set to 0.00001	To allow consideration of ND[a] concentrations
	Stepwise (forward)	Threshold value to enter: 0.05 Threshold value to remove: 0.10	Where each set of observations for potential fingerprint properties (tracers) is added stepwise to the model, to be removed when and if outperformed by a subsequently added set of observations
	Classes weight correction	Automatic	Where uneven numbers of observations exist for classes, this avoids penalising classes with lower numbers of observations in establishing the model
	Equality of covariance matrices	Yes	Assuming the covariance matrices associated with the classes are equal
	Significance level	5%	Confidence of 95% in correct classification
Validation	A set of observations to be used for model validation	Group variable[b]	Select user generated column of binary data that designates the observations to be used for validation of the model

[a] Where an element was retained in the working datasets although some concentrations were <LOQ (Section 5.2.4).
[b] Random generation option, varying *N* observations, was first used over multiple analysis runs until closer to satisfactory results were obtained. Then experimentation with user generated validation sample combinations was conducted.

Time available did not allow for further experimentation for intra-soil type discrimination. Nevertheless, to explore the potential for intra-soil type discrimination and using small datasets on the basis of soil depth and/or sub-type in future, it was considered the smallest and largest soil type datasets, soil type 1 and soil type 3 respectively, could be tested using the *Kruskal-Wallis* test, *Wilcoxon signed-rank* test for paired samples (subsoil and topsoil) and the *Mann-Whitney* test for non-paired samples (between sub-types of soils).

3.5 References

Allen, SE (1989). Chemical Analysis of Ecological Materials. Oxford, Blackwell.

Bowie, AR, Townsend, AT, Lannuzel, D, Remenyi, TA and van der Merwe, P (2010). "Modern sampling and analytical methods for the determination of trace elements in marine particulate material using magnetic sector inductively coupled mass-spectrometry." Analytica Chimica Acta **676**: 15-27.

Carter, J, Owens, PN, Walling, DE and Leeks, GJ (2003). "Fingerprinting suspended sediment sources in a large urban river system." The Science of the Total Environment **314-316**: 513-534.

Collins, A, Pulley, S, Foster, I, Gellis, A, Porto, P and Horowitz, A (2017). "Sediment source fingerprinting as an aid to catchment management: A review of the current state of knowledge and a methodological decision-tree for end-users." Journal of Environmental Management **194**: 86-108.

Collins, AL and Walling, DE (2002). "Selecting fingerprint properties for discriminating potential suspended sediment sources in river basins." Journal of Hydrology **261**: 218-244.

Collins, AL, Walling, DE and Leeks, GJL (1997a). "Source type ascription for fluvial suspended sediment based on a quantitative composite fingerprinting technique." Catena **29**: 1-27.

Collins, AL, Walling, DE and Leeks, GJL (1998). "Use of composite fingerprints to determine the provenance of the contemporary suspended sediment load transported by rivers." Earth Surface Processes and Landforms **23**: 31-52.

Collins, AL, Walling, DE, Stroud, RW, Robson, M and Peet, LM (2010). "Assessing damaged road verges as a suspended sediment source in the Hampshire Avon catchment, southern United Kingdom." Hydrological Processes **24**: 1106-1122.

Collins, AL, Zhang, Y, Walling, DE, Grenfell, SE, Smith, P, Grischeff, J, Locke, A, Sweetapple, A and Brogden, D (2012). "Quantifying fine-grained sediment sources in the River Axe catchment, southwest England: application of a Monte Carlo numerical modelling framework incorporating local and genetic algorithm optimisation." Hydrological Processes **26**: 1962-1983.

CSIRO. (2016). "Soil and Landscape Grid of Australia."

Dale, C, Brachfield, S, Hemming, SR and Flierdt, TVd (2008). Geochemical and E_{ND} results from Larsen-B ice shelf and Marie Byrd land sediments: implications for provenance tracing. Annual meeting, Houston.

Daniel, WW (1978). Applied Nonparametric Statistics. Boston, Houghton Hifflin Company.

Davies, PE, McIntosh, PD, Wapstra, M, Bunce, SEH, Cook, LSJ, French, B and Munks, SA (2005). "Changes to headwater stream morphology, habitats and riparian vegetation recorded 15 years after Forest Practices Code forest clearfelling in upland granite terrain, Tasmania, Australia." Forest Ecology and Management **217**: 331-350.

Davis, CM and Fox, JF (2009). "Sediment fingerprinting: Review of the Method and Future Improvements for Allocating Nonpoint Source Pollution." Journal of Environmental Engineering **135**(7): 490-504.

Eggins, SM, Woodhead, JD, Kinsley, LPJ, Mortimer, GE, Sylvester, P, McCulloch, MT, Hergt, JM and Handler, MR (1997). "A simple method for the precise determination of ≥40 trace elements in geological samples by ICPMS using enriched isotope internal standardisation." Chemical Geology **134**: 311-326.

Forest Practices Board (2005). Forest Practices Code. Hobart, Forest Practices Board.

Fu, B, Newham, LTH and Field, JB (2008). Influence of particle size on geochemical suspended sediment tracing in Australia. Sediment Dynamics in Changing Environments - 2008 Symposium of the International Commission on Continental Erosion, ICCE. Christchurch, IAHS-AISH Publication. **325:** 23-30.

Grant, JC, (Australia), NLP and Tasmania, FaFICo (1995). Forest soils of Tasmania : a handbook for identification and management Hobart, Forestry Tasmania.

Hagedorn, B, Cartwright, I, Raveggi, M and Maas, R (2011). "Rare earth element and strontium geochemistry of the Australian Victorian Alps drainage system: Evaluating the dominance of carbonate vs. aluminosilicate weathering under varying runoff." Chemical Geology **284**: 105-126.

Institute of Water Research, MSU. (2002). "RUSLE on line soil erosion assessment tool."

Krause, AK, Franks, SW, Kalma, SW, Loughran, RJ and Rowan, JS (2003). "Multi-parameter fingerprinting of sediment deposition in a small gullied catchment in SE Australia." Catena **53**: 327-348.

Laffan, MD, Grant, HC and Hill, RB (1998). "Some properties of soils on sandstone, granite and dolerite in relation to dry and wet eucalypt forest types in Northern Tasmania." Tasforests **10**: 49-58.

Laffan, MD, McIntosh, P and Neilson, WA (2003). "Forest soils derived from granite in northern Tasmania: an overview of properties, distribution and management requirements." Tasforests **14**: 1-14.

Marx, SK and Kamber, BS (2010). "Trace-element systematics of sediments in the Murray–Darling Basin, Australia: Sediment provenance and palaeoclimate implications of fine scale chemical heterogeneity." Applied Geochemistry **25**: 1221-1237.

Melaku, S, Dams, R and Moens, L (2005). "Determination of trace elements in agricultural soil samples by inductively coupled plasma-mass spectrometry: Microwave acid digestion versus aqua regia extraction." Analytica Chimica Acta **543**: 117-123.

Mineral Resources Tasmania (Undated). 1:25,000 Scale Digital Geology of Tasmania. Hobart.

Mineral Resources Tasmania (Undated). 1:500,000 Scale Digital Geology of Tasmania, Hobart.

Morelli, G, Gasparon, M, Fierro, D, Hu, W-P and Zawadzki, A (2012). "Historical trends in trace metal and sediment accumulation in intertidal sediments of Moreton Bay, southeast Queensland, Australia." Chemical Geology **300-301**: 152-164.

Nehyba, S, Adamova, M, Faimon, J, Kuchovsky, T, Holoubek, I and Zeman, J (2010). "Modern fluvial sediment provenance and pollutant tracing: a case study from the Drevnice River Basin (eastern Moravia, Czech Republic)." Geologica Carpathica **61**(2): 147-162.

Oliver, RL, Hart, BT, Olley, J, Grace, M, Rees, C and Caitcheon, G (1999). The Darling River: Algal Growth and the Cycling and Sources of Nutrients. Murray-

Darling Basin Commission Project M386, CRC for Freshwater Ecology; CSIRO Land and Water.

Olley, J and Caitcheon, G (2000). "Major element chemistry of sediments from the Darling-Barwon River and its tributaries: implications for sediment and phosphorus sources." Hydrological Processes **14**: 1159-1175.

Pengfei, D and Walling, D (2017). "Fingerprinting surficial sediment sources: Exploring some potential problems associated with the spatial variability of source material properties." Journal of Environmental Management **194**: 4-15.

Petherick, LM, McGowan, HA and Kamber, BS (2009). "Reconstructing pathways for late Quaternary dust from eastern Australia using the composition of trace elements of long travelled dusts." Geomorphology **105**: 67-79.

Phillips, JM, Russell, MA and Walling, DE (2000). "Time-integrated sampling of fluvial suspended sediment: a simple methodology for small catchments." Hydrological Processes **14**(14): 2589-2602.

Poleto, C, Merten, GH and Minella, JP (2009). "The identification of sediment sources in a small urban watershed in southern Brazil: An application of sediment fingerprinting." Environmental Technology **30**(11): 1145-1153.

Rowan, JS, Goodwill, P and Franks, SW (2000). Uncertainty estimation in fingerprinting suspended sediment sources. Tracers in geomorphology. I. D. L. Foster. Chichester, Wiley.

Roy, PD, Morton-Bermea, O, Hernandez-Alvarez, E, Pi, T and Lozano, R (2010). "Rare earth element geochemistry of the Late Quaternary tephra and volcano-clastic sediments from the Pachuca sub-basin, north-eastern Basin of Mexico." Geofisica Internacional **49**(1): 3-15.

Taylor, VF, Toms, A and Longerich, HP (2002). "Acid digestion of geological and environmental samples using open-vessel focused microwave digestion." Analytical and Bioanalytical Chemistry **372**: 360-365.

Viers, J, Roddaz, M, Filizola, N, Guyot, J-L, Sondag, F, Brunet, P, Zouiten, C, Boucayrand, C, Martin, F and Boaventura, GR (2008). "Seasonal and provenance controls on Nd-Sr isotopic compositions of Amazon rivers suspended sediments and implications for Nd and Sr fluxes exported." Earth and Planetary Science Letters **274**: 511-523.

Walling, DE (2005). "Tracing suspended sediment sources in catchments and river systems." Science of the Total Environment **344**: 159-184.

Wang, Q, Li, Y and Wang, Y (2011). "Optimizing the weight loss-on-ignition methodology to quantify organic and carbonate carbon of sediments from diverse sources." Environmental Monitoring and Assessment **174**: 241-257.

Yu, Z, Robinson, P and McGoldrick, P (2001). "An Evaluation of Methods for the Chemical Decomposition of Geological Materials for Trace Element Determination using ICP-MS." Geostandards Newsletter **25**(2-3): 199-217.

Yu, Z, Robinson, P, Townsend, A, Münker, C and Crawford, AJ (2000). "Determination of High Field Strength Elements, Rb, Sr, Mo, Sb, Cs, Tl and Bi at ng g^{-1} Levels in Geological Reference Materials by Magnetic Sector ICP-MS after $HF/HClO_4$ High Pressure Digestion." Geostandards Newsletter **24**(1): 39-50.

Chapter 4

Landscape physiography of the Esk Rivers basin and change over the Holocene quantified by GIS.

Figure 4.1: The flanks of Ben Lomond, looking WNW from mid-altitude in the upper South Esk catchment.

4.1 Physiographic setting

The Esk Rivers basin, including the Meander, Brumbys-Lake[1], Macquarie, South Esk and North Esk river catchments, occupies 10,205 km^2 (16%) of the main island of Tasmania (Figure 1.3). The Esk Rivers basin drains via the South and North Esk Rivers into the upper reach of the Tamar estuary, approximately 70 km inland from the estuary outlet at Bass Strait in the north. The Tamar estuary itself was discussed in detail in Chapter 1. The immediate estuary catchment comprises 1122 km^2, however its low-lying reach is of little interest compared to the extensive riverine basin, which receives closer examination here.

The North Esk catchment occupies 1064 km^2. The South Esk basin occupies 9141 km^2 and includes the Meander (1555 km^2), the Macquarie (2700 km^2), the Brumbys/Lake (1394 km^2) and South Esk (3345 km^2) river catchments.

Climates and topographic settings vary widely in the Esk Rivers Basin. It reaches south from the Tamar estuary and Launceston across the northern Midlands plains almost to Oatlands, and west from Meander and the Great Western Tiers to St Marys near the east coast. It includes much of the northeast highlands in the upper North and South Esk catchments and lies between sea level and 1570 m elevation. Continuous plains are limited to the northern Midlands between Launceston and Tunbridge (19 km north of Oatlands, Figure 1.3), occupying the Midlands graben and extending into the South Esk River valley (Davies, 1965).

[1] Water diversion from the Great Lake for the Poatina/Trevallyn Hydro-electric power scheme intermittently extends the Brumbys-Lake catchment onto the Central Plateau (Derwent catchment; Figure 3.5), however the natural catchment has been used in the project datasets.

Tasmania lies partly in the path of the westerly zonal wind system known as the Roaring Forties and has a marked west to east rainfall gradient, whereby precipitation is much lower in eastern lowland regions in the rain shadow of the western highlands (Langford, 1965; Jackson & Brown, 2005). Consequently, climates and storm response river flows also vary across the Esk Rivers basin. The western region and higher elevation northeastern regions have a winter-wet seasonal distribution of rainfall and higher annual precipitation, for example Deloraine (elevation 237 m) with an average annual precipitation 946 mm (Figure 4.2).

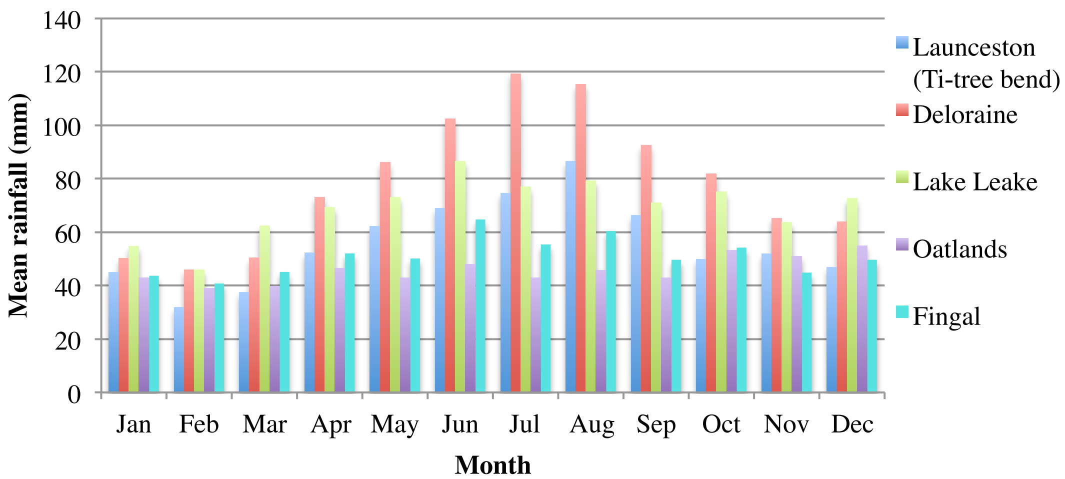


Figure 4.2: Precipitation distribution in the Esk Rivers basin. Source: Bureau of Meterology (2013). Data are from extant rainfall stations with records since the 1880s, excepting Launceston (Ti-tree bend), with records from 1980-open. Note: Oatlands is just outside the catchment but no alternative long-term data from the distal extent of the northern Midlands plains are available.

The rainfall of the Midlands plains, including the broad plains of the South Esk River's middle reaches, has a relatively even distribution throughout the year. However, it is the driest region of the basin, where potential evaporation exceeds precipitation (Langford, 1965). For example, the annual average precipitation of Oatlands (elevation 406 m) is 549 mm. At the pilot study catchment outlet, Fingal (elevation 237 m; Figure 1.3) the lowlands have an annual average precipitation of 610 mm, while in nearby alpine areas of the study catchment, where there are no extant weather stations, rainfall exceeds 1,500 mm per annum (Bureau of Meteorology, 2013), with a winter-wet seasonal distribution.

The most variable precipitation is in the east of the Esk Rivers Basin including the north-east highlands. For example, see St Marys in the South Esk catchment and Lake Leake in the Macquarie catchment (Figure 4.2). This region is subject to high precipitation storm events from tropical troughs and cut-off cyclones, particularly in the late summer and early autumn months (Langford, 1965). Cyclic climatic conditions of drought followed by drought-breaking rains affect the Esk Rivers region, enhancing erosion processes associated with land degradation (Bobbi *et al.*, 1996).

Within the South Esk River catchment, the pilot study area of 1016 km^2 extends from the vicinity of the town of Fingal to include the St Marys district and much of the northeastern Tasmania highlands, from broad river valleys to some of the rugged mountain tops of northeast Tasmania. According to *Land systems* data, the elevation ranges from 220 m at the catchment outlet 2.3 km north of Fingal, at the confluence of the South Esk and Break O'Day Rivers, to 1570 m elevation on Legges Tor northwest of Fingal (Department of Primary Industries and Water, 1978-1989). Elevations are >700 m lower on the highest hills to the east of St Marys than the mountains of the upper South Esk catchment. According to GIS analysis within the study area, the upper

South Esk sub-catchment occupies 794 km^2 or 78% of the land area while the Break O'Day catchment occupies 222 km^2 or 22% of the southeastern region of the study area.

From digital geological data (Mineral Resources Tasmania, Undated), the inferred ages of the surface geology in the study area ranges from 440 million years to present, comprised of Ordovician-Devonian (sedimentary and acid igneous rocks) to Jurassic (basic igneous rocks) and Quaternary (alluvium and colluvium). From *Vegetation of Tasmania* (*TasVeg*) data, native vegetation (including regenerating native vegetation) co-dominates with silviculture plantations across the mid- and upper slopes of the catchment, while agriculture/exotic vegetation dominates lower elevations (Department of Primary Industries & Water & Department of Environment, 2002; Department of Primary Industry, 2013). The vegetation cover/land use mosaic exists in a complex topographic patchwork, particularly in the mid- to lower elevations.

The review in Chapter 2 considered the magnitude and rate of landscape change in the study basin over recent earth history and since the migration of the first people to Tasmania from the literature. However, to improve understanding of destabilisation processes today, landscape change and instability over time were analysed from paper maps and digital mapping, with particular focus on an upper catchment pilot study area of >1,000 km^2. Digital data sources and other metadata are shown in Appendix 1.

4.2 Pre-European vegetation

Probable pre-European vegetation distribution, modeled by a team of Tasmanian experts (Anne Kitchener, pers. comm., February 2010), was compiled in broad vegetation classes (Department of the Environment, 2002). The data are shown in Table 4.1, and Figures 4.3 and 4.4 below. Minor discrepancies in total areas quoted reflect the nature of the data.

Vegetation formations analogous to savannah grasslands featured in the lowlands of the Macquarie and South Esk catchments, flanked by shrubby forests that extended around the head of the Tamar estuary and over much of the South Esk catchment, while structures including closed forests cloaked the higher elevations of the basin (Figures 4.3 & 4.4).

Table 4.1: Estimated Pre-European vegetation in the Esk Rivers Basin (% catchments). Source: Department of the Environment, Water, Heritage and the Arts, 2002.

Catchment (%)	Macquarie	Meander	North Esk	South Esk	Brumbys-Lake	Basin
Forest (medium tree understorey)	0	0	47	10	0	8
Forest (low tree understorey)	10	29	20	24	38	23
Forest/ woodland (shrubby)	31	63	33	55	37	45
(Forest/ woodland (grassy)	60	0	0	11	6	21
Highland shrubs & low trees	0	7	0	0	19	4
Highland shrubs & grasses	0	1	0	0	0	<1

However, the coarse resolution of this mapping does not depict the mosaic pattern of grassy ecosystems that was likely throughout the Midlands in the late Holocene (Kirkpatrick & Bridle, 2007). Forests with tall upper strata grew in the humid sub-montane upper reaches of the Meander, South Esk and North Esk catchments. Where

30-70% canopy cover is represented in the upper North and South Esk catchments of the northeast highlands on the map, forest community mosaics with Aboriginal meadows existed, as studied by Ellis (1985). Chains of grassy pastures also existed to the west and southwest of Launceston (for example Breen, 2001).

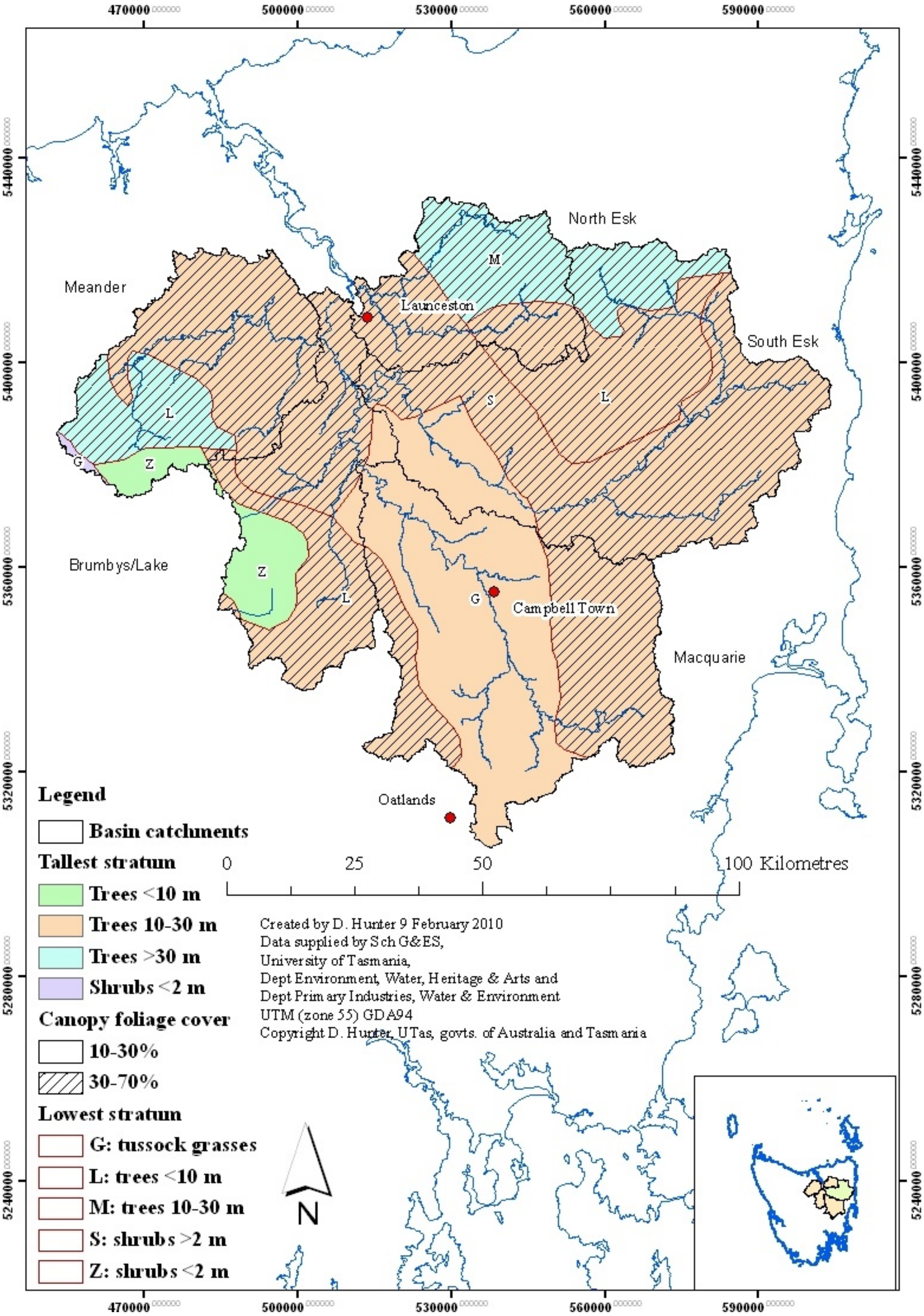


Figure 4.3: Estimated pre-European Holocene vegetation of the Esk rivers basin. Digital data source: Department of the Environment, Water, Heritage and the Arts, 2002. Note: the extensive plains region of grassy woodlands known as the Midlands is represented by the unhatched area marked “G” (tussock grasses) that includes Campbell Town.

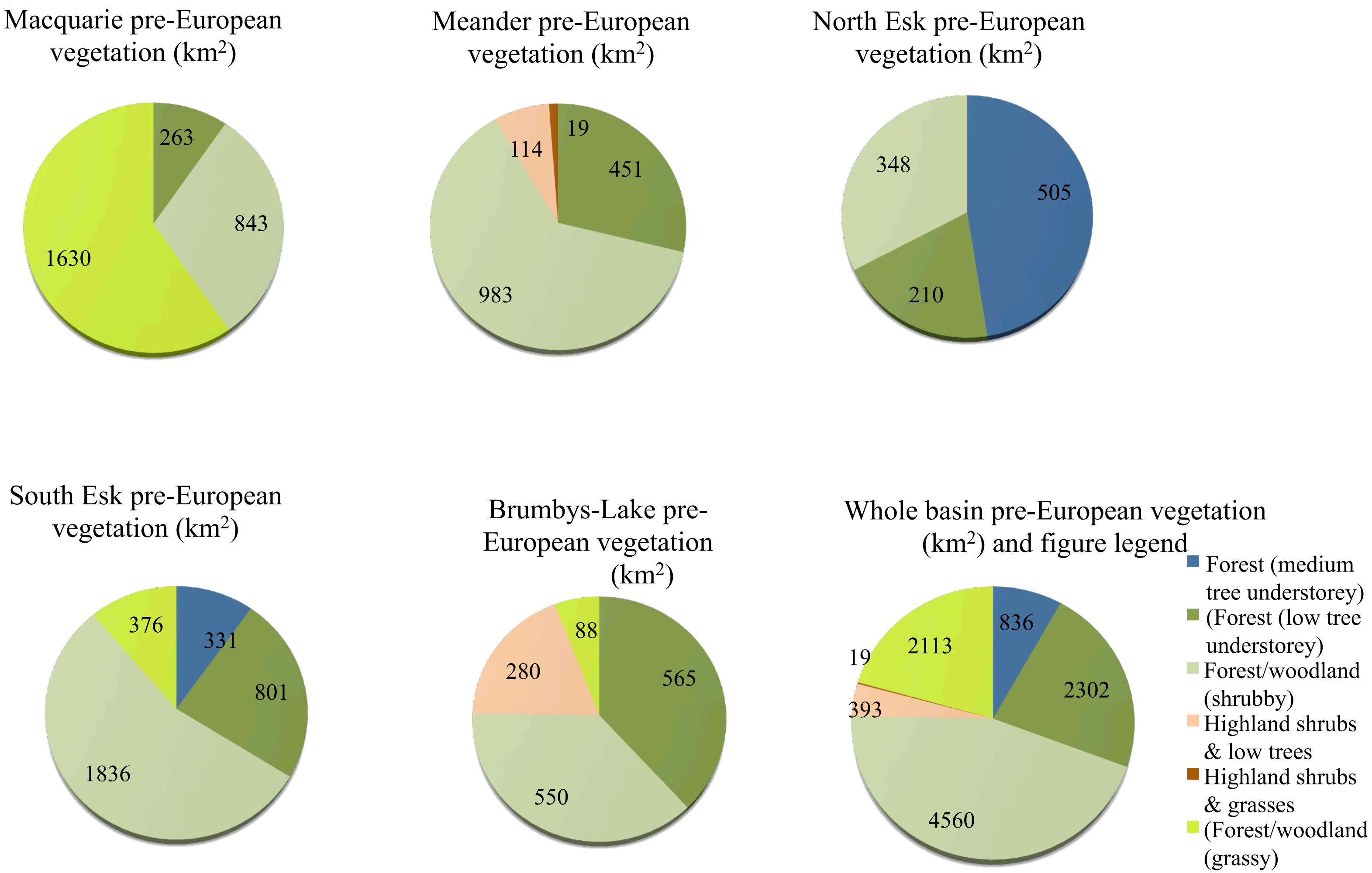


Figure 4.4: Pre-European vegetation in the Esk Rivers basin and its catchments (km^2). Source: Dept. Environment, Water, Heritage & Arts, 2002.

4.3 Post-European colonisation landscape changes

Further to the literature review in Chapter 2 (2.1.2), several stages of landscape change from the period before digital data were available could be reconstructed and quantified from digitised paper maps.

Much of the Esk Rivers basin, the second rural settlement area in Australia after the Cumberland Plains in New South Wales, was under European settlement by 1825 (Scott, 1965). In this year the colony of Tasmania separated administratively from New South Wales (Fensham, 1989; Morgan, 1992) (Table 4.2; Figures 4.4 & 4.5).

Table 4.2: Cumulative alienation of land in the Esk Rivers basin (% catchments). Source: Scott, (1965). Note: study basin area percentages have been calculated from digitisation of a paper map and are approximate.

Catchment (%)	Macquarie	Meander	North Esk	South Esk	Brumbys-Lake	Basin
1824	25	6	16	14	17	16
1854	63	31	17	37	35	41
1914	87	74	61	60	68	71
1964	90	74	63	61	72	73

By 1843, Crown land sales had replaced grants as incentives and total alienation in Tasmania reached 8,094 km^2 (Lakin, 1967). Privately owned land had extended into almost all the Midlands plains of the Esk Rivers basin, the upper Derwent valley and much of the east coast (Scott, 1965; Lakin, 1967). Indeed, by 1st January 1850, privately owned land covered 11,020 km^2 of Tasmania, while the area of Crown land held under depasturing (grazing) licences was 5,406 km^2 (Lakin, 1967).

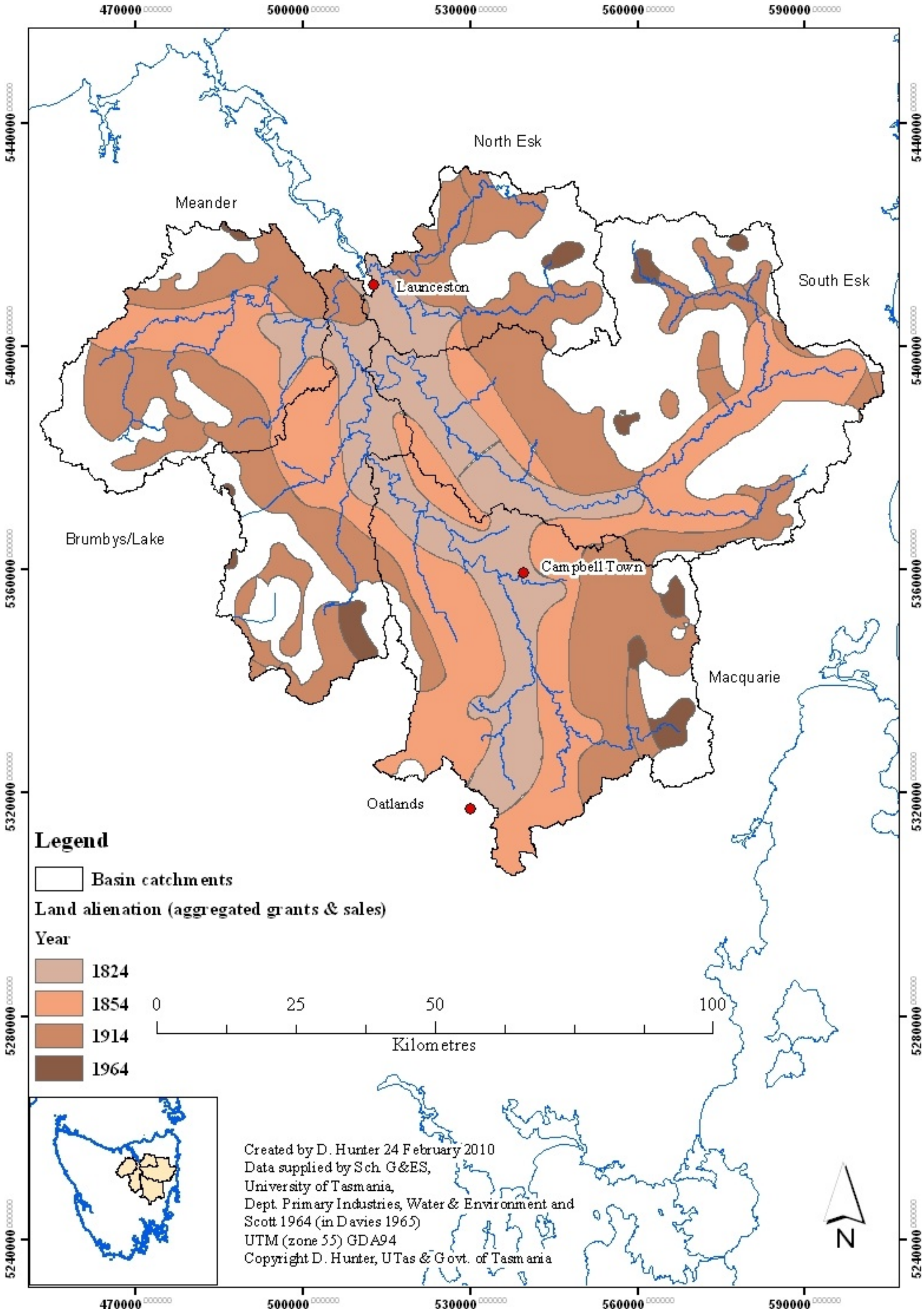


Figure 4.5: Land alienation in the Esk rivers basin to 1964. Blank areas on the map remained vested in the Crown at 1965; most of this land remains so vested today. Paper map source: Scott, 1965.

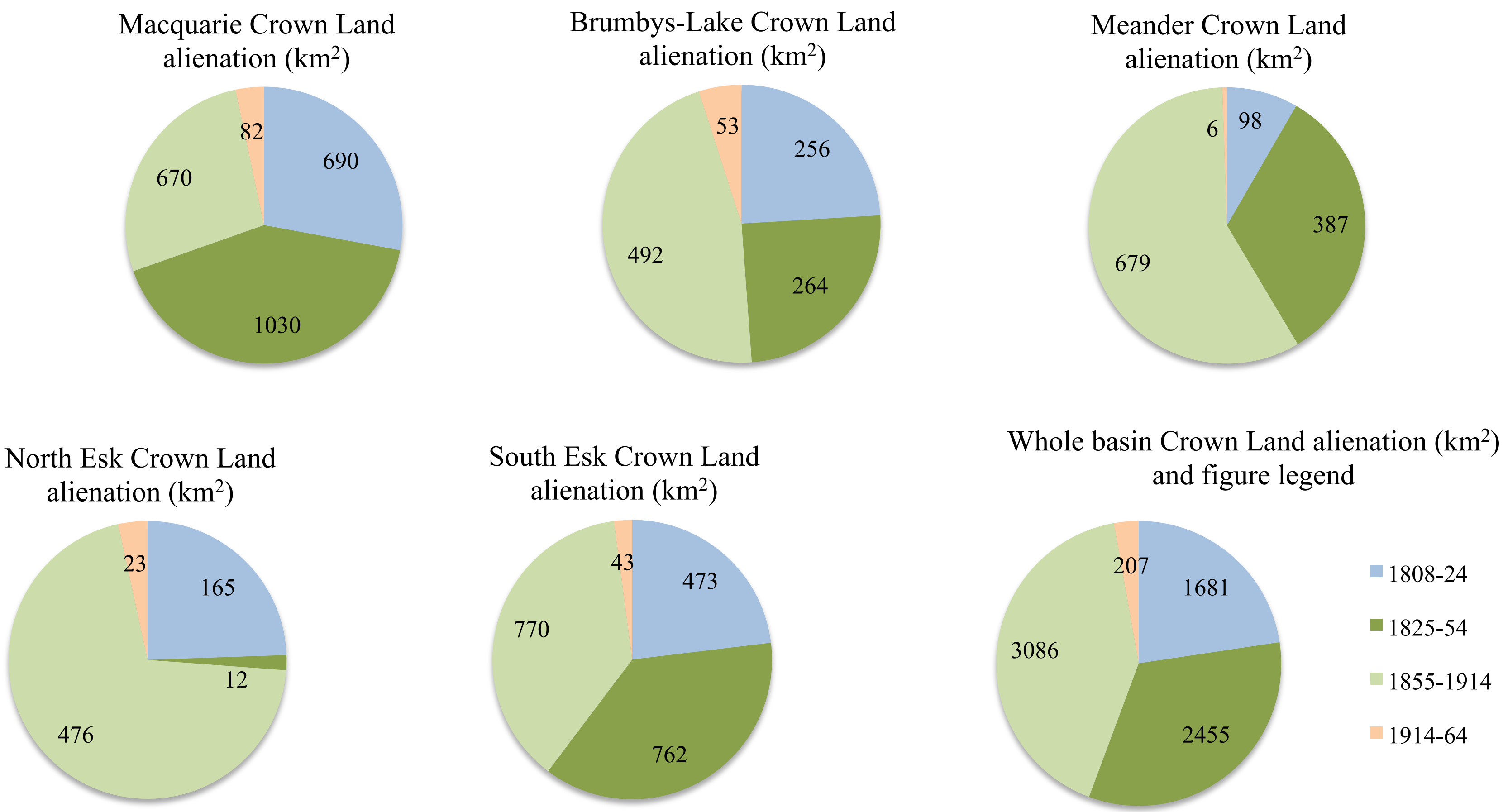


Figure 4.6: Proportion and progression of total alienated land in the Esk Rivers basin and its catchments over the period of European colonisation (km^2). Source: Scott, 1965.

Permanent settlement lagged land alienation in the Midlands until after 1911 (Scott, 1965), reflecting the nature of sheep husbandry of the times, with flocks roaming freely over the large grazing runs. The Closer Settlements Acts 1906-08 allowed for division of large estates that had become regarded as underutilised (Australian Bureau of Statistics, 1910). Annual alienation reduced with availability of land in Tasmania between 1910 and 1964 and had all but ceased by 1965 (Cocking, 1985; Figures 4.5 to 4.7). On this basis, alienation of Crown land across the state was effectively complete only about 160 years after settlement, although significantly, it took decades less in the Esk Rivers basin (Figure 4.7).

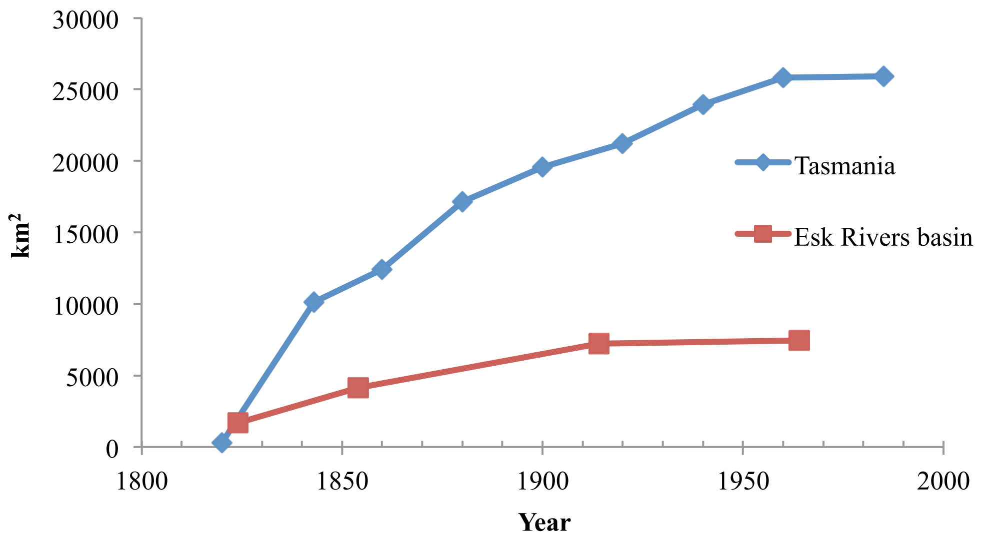


Figure 4.7: Aggregated land alienation, Tasmania and Esk rivers basin. Source: Scott, (1965), Tasmanian Year Book No. 1 (Lakin, 1967) and Tasmanian Year Book 1985 (Cocking, 1985). Note: study basin areas have been calculated from digitisation of a paper map and are approximate.

Lands close to the port of Launceston as well as the open plains of the Midlands were settled both more rapidly, and ultimately more completely, than other catchments across

Tasmania. Only 10% of the original Crown land of the Macquarie catchment remained uncommitted by 1964 (Table 4.2). The early utilisation of the Esk Rivers basin for agricultural production, disproportionate relative to its proportion of Tasmania's landmass, reflected its large share of land suitable and readily available for agriculture. Most of today's private tenure in the basin was established prior to 1914 and by 1964, private ownership had reached 73% or 7,429 km^2 (Figures 4.5 & 4.6). The extent of clearance of the Esk Rivers basin and remaining native vegetation at 1964 is shown in Figures 4.8 and 4.9 (below).

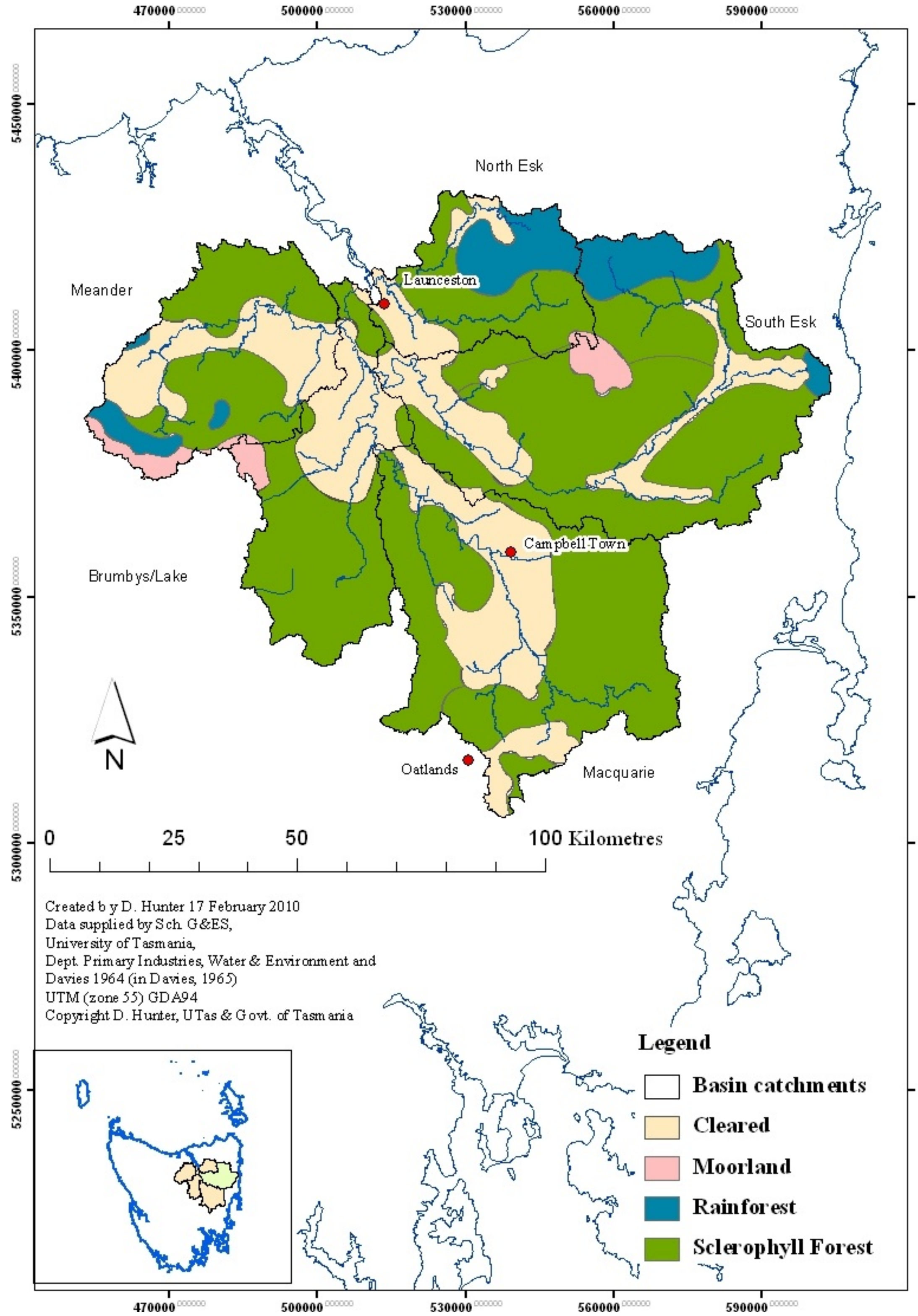


Figure 4.8: Vegetation of the Esk rivers basin in 1964. Source: Davies, 1964, in Davies, 1965. Note: "sclerophyll forest" includes grassy and shrubby woodlands; "moorland" consists of alpine vegetation.

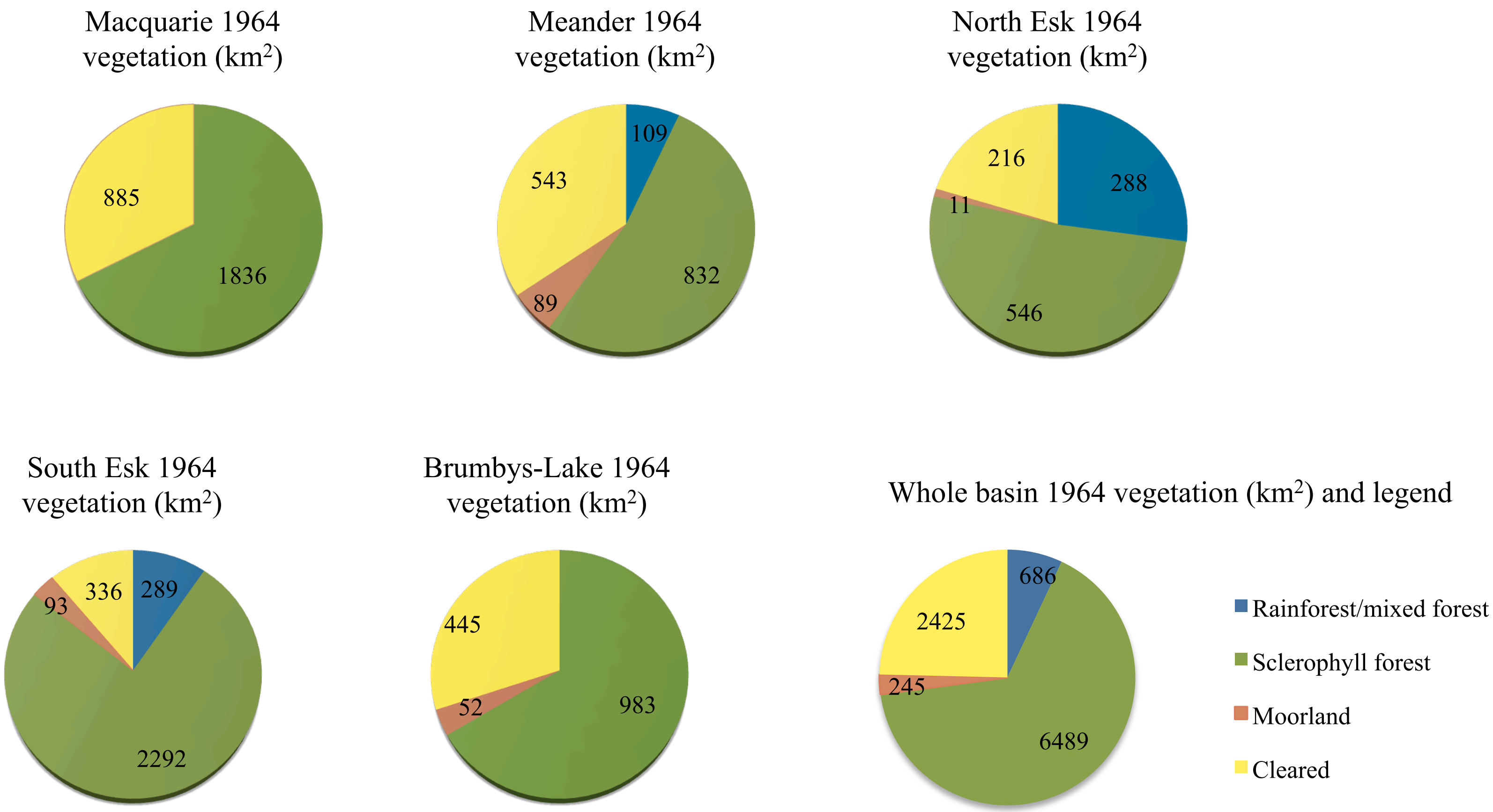


Figure 4.9: Areas of native vegetation and cleared land in the Esk Rivers basin catchments at 1964 (km^2). Source: Davies, 1965. Note: "sclerophyll forest" includes grassy and shrubby woodlands.

In his broad classification of vegetation, Davies (1965) included grassy and shrubby woodlands in “sclerophyll forest,” and “cleared” included a mosaic of introduced pastures and cropping land with native grassland and woodland remnants. Montane vegetation is expressed as “moorland.”

Table 4.3: Vegetation in the Esk Rivers Basin at 1964 (% catchments). Source: Davies, 1964, in Davies, 1965. Note: “sclerophyll forest” includes grassy and shrubby woodlands.

Catchment (%)	Macquarie	Meander	North Esk	South Esk	Brumbys-Lake	Basin
Rainforest/ mixed forest	0	7	27	10	0	7
Moorland	0	6	1	3	3	2
Sclerophyll forest	67	53	51	76	66	66
Cleared	33	35	20	11	30	25

At 1964, Brumby’s-Lake, Macquarie and Meander catchments had the highest proportions of cleared land, in contrast to the South and North Esk catchments where clearing was hindered by a higher proportion of heavily wooded, elevated country.

It can be seen between colonisation and 1964, much agricultural country was cleared at the expense of forest cover (shown as vegetation with over 30% canopy in Pre-European vegetation, Figure 4.3), especially the tall and medium forests in the upper Meander and Brumbys/Lake catchments, in the lowlands of the middle and upper reaches of the South Esk catchment and in Launceston’s near hinterland. Tall forest was reduced in the St Patricks River sub-catchment in the North Esk catchment. Elsewhere, grassy woodland country (less than 30% canopy in Figure 4.3) has been cleared. Nevertheless, in 1964, native vegetation still flanked the plains on the surrounding hillslopes, clothing the more distal hinterlands as well as the Esk Rivers highlands (Figure 4.8).

On the other hand, in comparing the maps of Pre-European vegetation (Figure 4.3) and 1964 vegetation (Figure 4.8), sclerophyll forests and woodlands had reclaimed quite substantial parts of the Midlands, particularly in the Macquarie and South Esk catchments. Consistent with the present review (Chapter 2), it appears likely that these incursions reveal areas of the Midlands that were previously in ecotype disclimax, having been kept in check by Aboriginal fire, in contrast to much of the Midlands that required no Aboriginal fire to maintain the ecosystems, as suggested by Fensham and Kirkpatrick (1992) (Section 2.1). These findings suggest prior to European occupation, the Midlands landscape was partly an Aboriginal cultural artefact and partly controlled by climate, browsing and conditioned exclusion of eucalypt seedlings.

4.4. Contemporary land use and vegetation

Esk Rivers basin recent (2001/02) and contemporary land use data (2013) were clipped from the state-wide digital datasets and are shown in Figures 4.10 and 4.11 and summarised in Tables 4.4 and 4.5. Colour coding is consistent between the figures to facilitate cross-referencing. Comparative data are shown in Figure 4.13, followed by *WaterCAST* model sediment yield mapping (Figure 4.14). Recent land use changes were examined more closely in the pilot study area (Figures 4.15 to 4.17).

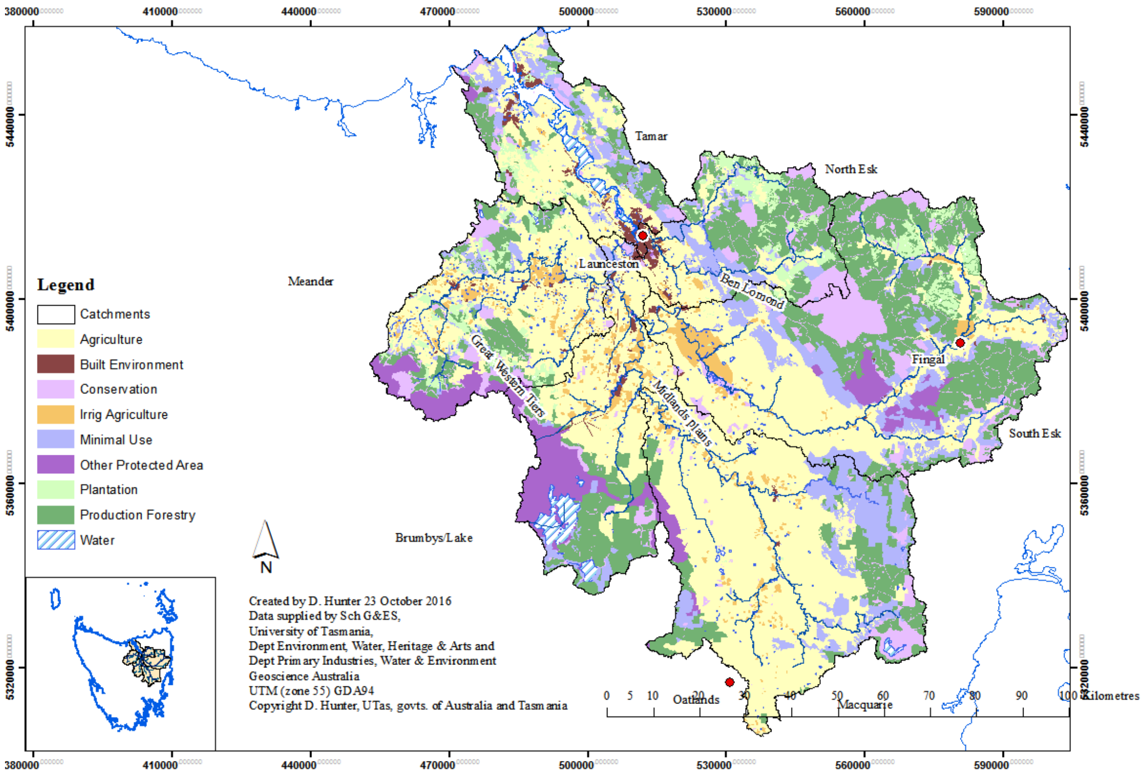


Figure 4.10: Recent land use (2001/02) in the Tamar basin.

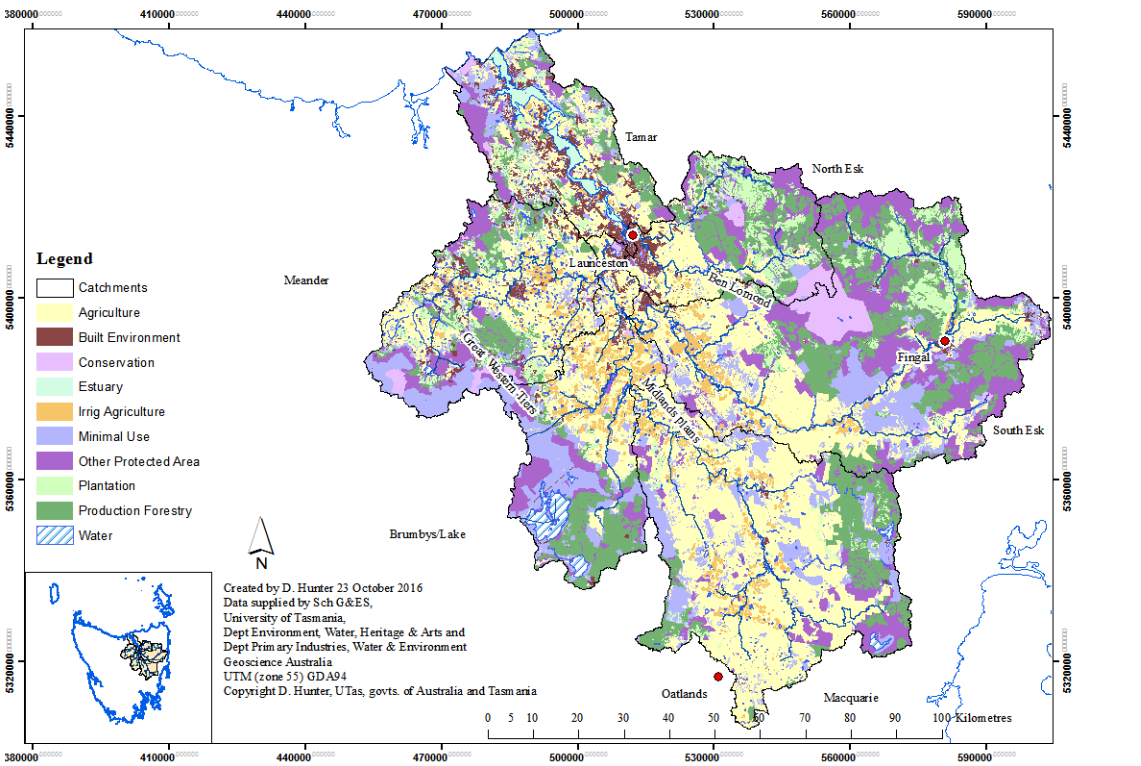


Figure 4.11: Contemporary land use (2013) in the Tamar Basin.

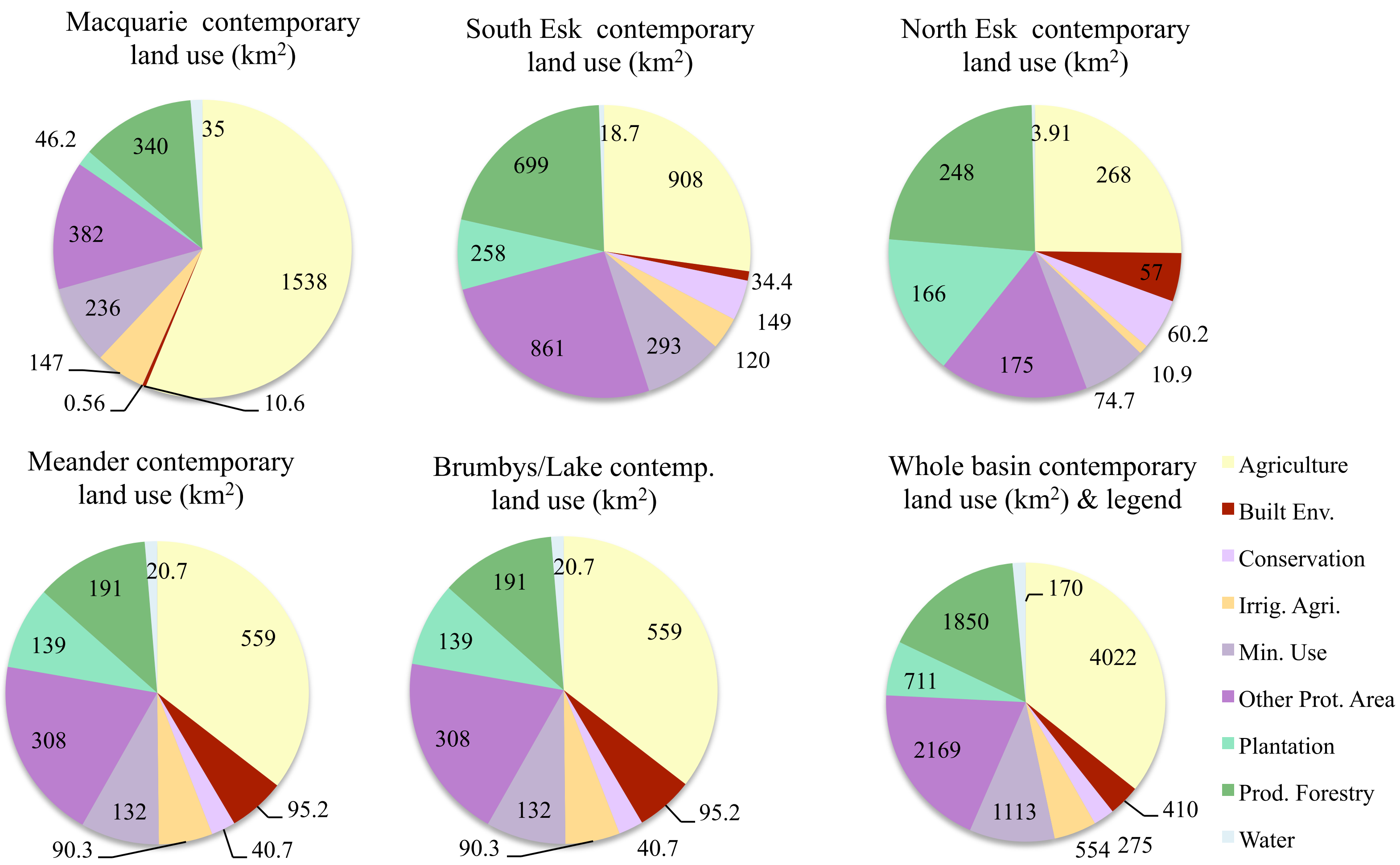


Figure 4.12: Contemporary land use (2013) in the Esk rivers basin (km^2). Tamar catchment data omitted (shown in Table 4.5).

Table 4.4: Recent land use (2001/02) in the Tamar basin (% catchments).

Catchment (%)	Mac-quarie	Meander	North Esk	South Esk	Brumbys /Lake	Tamar	Basin
Agriculture	65	49	25	34	40	43	45
Irrig. agric.	2	6	1	4	6	1	4
Built env.	0	1	3	0	2	6	1
Conservation	4	8	12	12	4	8	8
Other prot. area	2	8	0	4	18	1	6
Min. use[a]	14	5	14	13	5	17	11
Prod. forest	12	15	32	29	21	16	21
Plantation	0	7	12	4	0	4	4
Water	1	1	0	0	6	4	1

[a]*Minimum Use* category was designated by the originators of the data and consists largely of little used bushland.

Table 4.5: Contemporary land use (2013) in the Tamar basin (% catchments).

Catchment (%)	Mac-quarie	Meander	North Esk	South Esk	Brumbys /Lake	Tamar	Basin
Agriculture	56	35	25	27	28	30	36
Irrig.agric.	5	6	1	4	12	1	5
Built env.	0	6	5	1	3	15	4
Conservation	0	3	6	4	1	1	2
Other prot. area	14	20	16	26	20	13	19
Min. use	9	8	7	9	14	15	10
Prod. forestry	12	12	23	21	16	12	16
Plantation	2	9	16	8	1	7	6
Water	1	1	0	1	6	0	2

Tamar data were added for land use change comparisons in these tables and Figure 4.13 below. Classifications were simplified for analysis and presentation. For example, grazing and cultivation are combined as *Agriculture*.

Notwithstanding some inherent difficulties in direct comparisons between the datasets due to classification category changes, there are important differences in land use apparent within the last decade. They include reductions in agricultural land, formal conservation areas and production (native forest) forestry. Land use classification increases include plantations and informal conservation areas (e.g. in application of the Forest Practices Code). Agriculture has intensified, particularly note the increase in irrigated agriculture in the figures and tables.

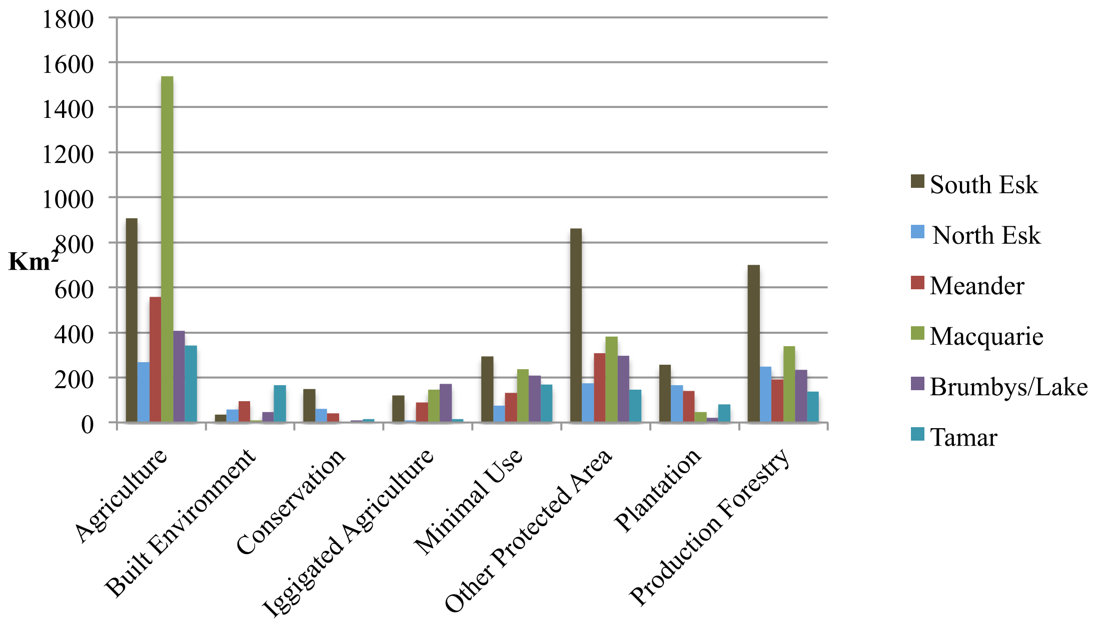


Figure 4.13: Contemporary Tamar basin land use (2013) by catchment (km^2).

Agriculture remains the largest land use today, by area occupied in the Esk Rivers basin and its component catchments. Irrigated (intensive) agriculture is now particularly important in the lower elevations of the Meander, Macquarie and the lower Brumbys/Lake and South Esk catchments. Remnant native grassy ecosystems are still embedded in the agricultural land of the Midlands and some restoration of native vegetation corridors is underway (discussed below). Production forestry lands and areas of native forest converted to tree plantations now dominate the northeastern highlands of the upper Esk Rivers catchments and the upper Brumbys/Lake catchment on the Central Plateau, with embedded streamside and other informal reserves ("Other protected land”). Much of the remaining “Conservation” (formally protected) land consists of mountain peaks and alpine plateaux. Much of the “Other protected area” in the upper Brumbys/Lake catchment is land vested in Hydro Tasmania, associated with hydro-electric infrastructure. The data illustrate the conversion of most land suitable for agriculture and grazing during the last 200 years, and the consequent reduction in native forest and woodland cover since 1964 (Figure 4.8) discussed in the preceding review.

Forestry warrants special examination as its rapid growth and practices have been socio-politically contentious since the 1970s. Most forests of potential commercial value lie outside the conservation areas shown on the 2001 land use map (Figure 4.10), while an increase in “Other protected” areas since 2002/03 (2013, Figure 4.11) represent mainly forestry management zones within production areas, progressively mapped or implemented under the Forest Practices Code (Green, 2004).

Plantations have taken the place of (or augmented) traditional farming uses on private land holdings and have further reduced the extent of wet forests on both private and public land. Excluding pre-1995 plantations, 394 km^2 of plantations displaced native forest across Tasmania between 1995 and 2006, while 571 km^2 displaced farming land uses (Private Forests Tasmania, 2007). Total plantation coverage in the Esk Rivers basin at 2001/02 was 370 km^2, increasing to 630 km^2 by 2013. Some 80 km^2 had been established in the Tamar catchment itself from the 2013 data. Tasmania’s 2,542 km^2 of plantations at December 2006 (public and private land) represented 14% of Australia’s total plantation estate and covered 3.7% of Tasmania (Private Forests Tasmania, 2007). By 2010 they covered 3,420 km^2 or 5.0% of the state (Forest Practices Authority, 2012; Pitt and Sherry & Esk Mapping and GIS Services, 2012).

Forestry in the high rainfall upper Esk Rivers and Meander catchments, has been associated with the production of 38% of the annual sediment flux to the Tamar Estuary, the highest yield by land use for land area (*WaterCAST* modelling, BMT WBM Pty Ltd, 2010, Figure 4.14).

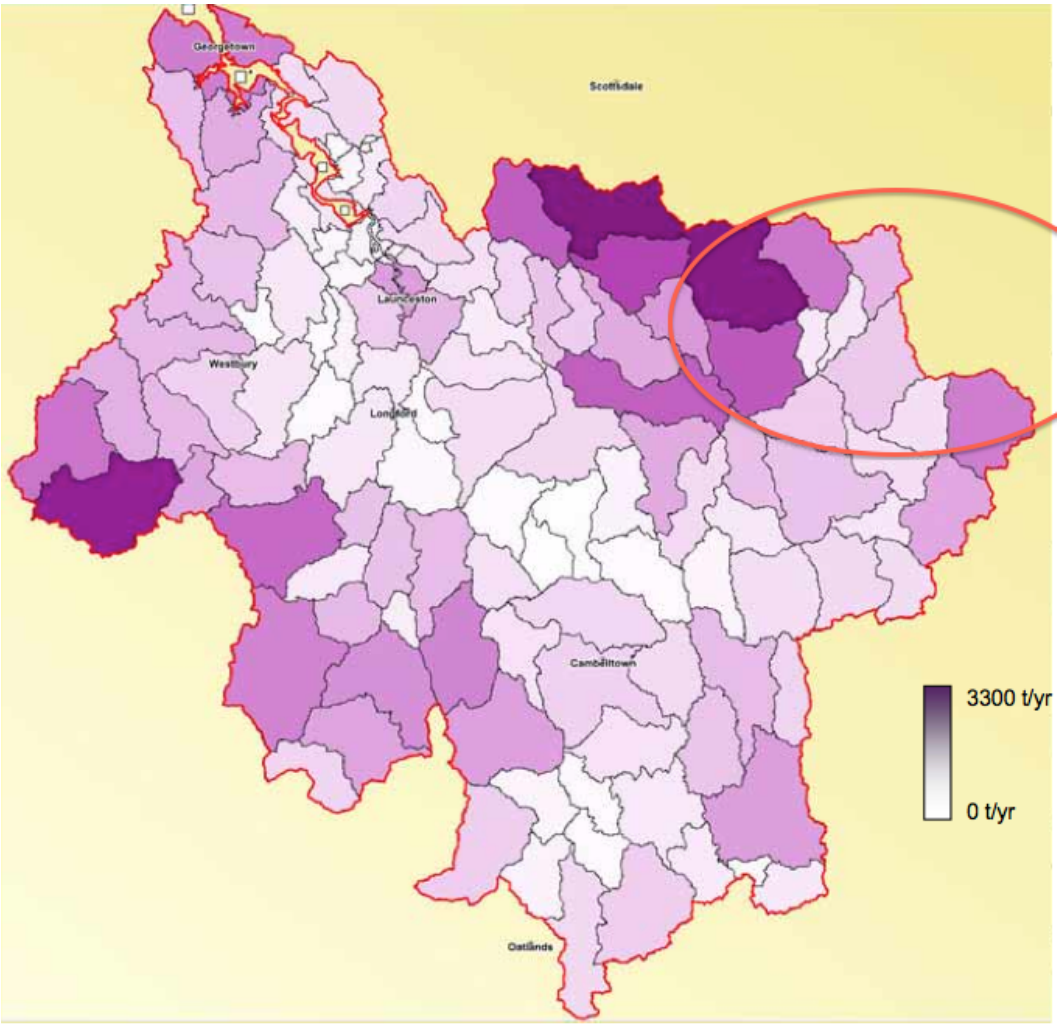


Figure 4.14: The Tamar Basin *WaterCAST* model of total suspended sediment (TSS) yields (t/year) (BMT WBM Pty Ltd, 2010, reproduced by permission of NRM North). Subdivisions of river catchments (TSS t/yr) within the pilot study area are shown circled. High sediment yield (deep purple) was found for the upper Meander (far left/west), the upper South Esk catchments and adjoining upper North Esk (north-east).

The areal subdivisions used in the TSS modelling shown in Figure 4.14 differed from the CFEV riverine sub-catchments used in the present study's GIS. There was insufficient time to manipulate the data for further analysis in the project GIS. However, erosion hazard mapping that was used to model TSS yield is covered in Chapter 5.

The following figure examines land use changes in the pilot study area (Figure 4.15), further depicted in maps a decade apart (Figures 4.16 & 4.17).

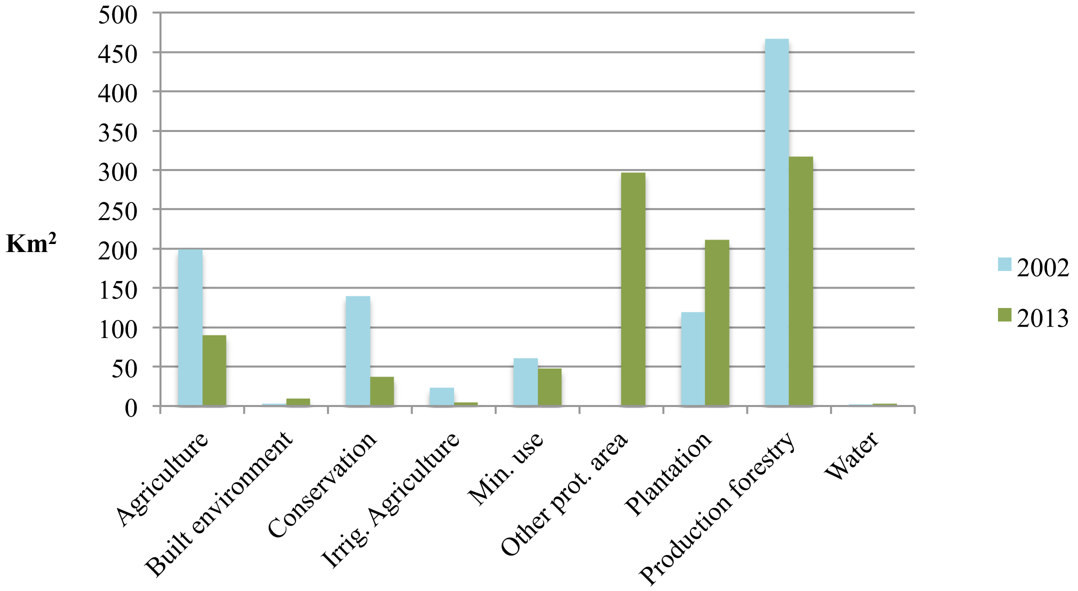


Figure 4.15: Recent land use changes in the upper South Esk (pilot study area) catchment.

The trends in recent land use change found across the Esk Rivers basin are marked in the upper South Esk catchment, with changes in conservation tenure and the forestry mix of particular interest. However, while production forestry and plantations have such a substantial coverage (>50%), conservation land use (3.7%) still occupies the most topographically superior position in the landscape (Ben Lomond National Park). While large areas of the valley floors that were once agricultural land underwent conversion to plantation between 2002/03 to 2013 (Figures 4.16 & 4.17), the reverse may now be observed throughout the Esk Rivers basin since 2013.

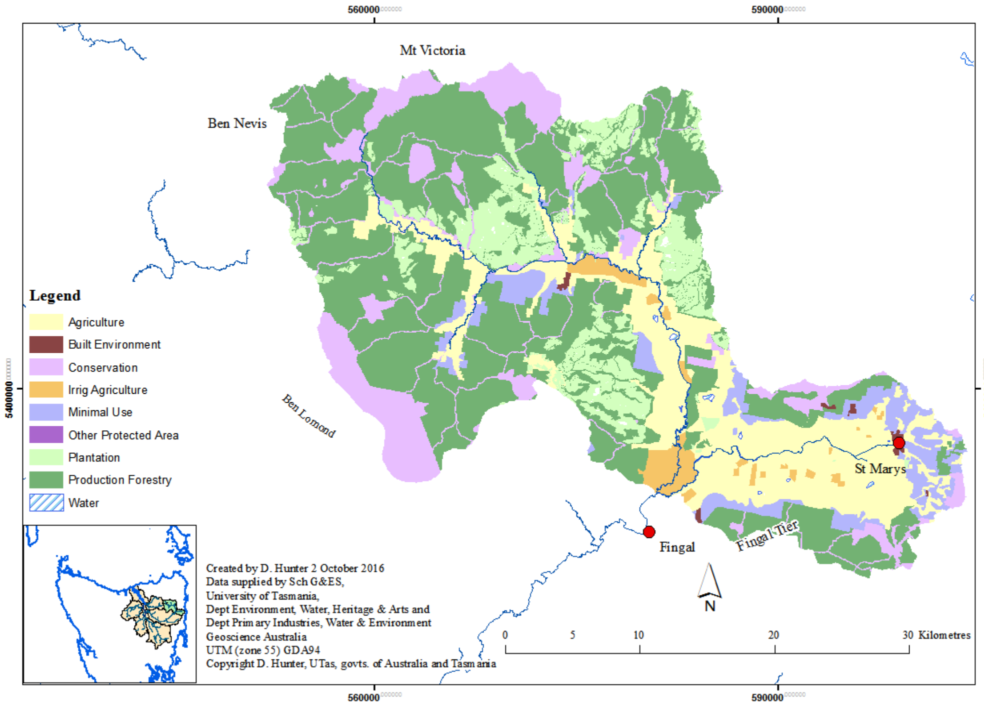


Figure 4.16: The Upper South Esk catchment land use (2002).

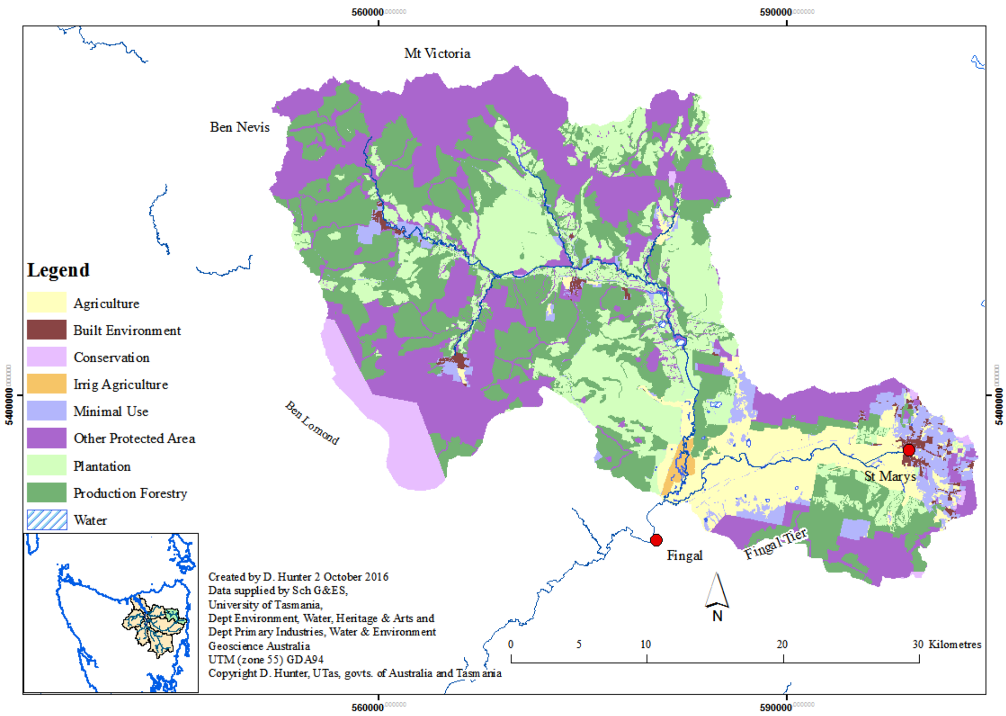


Figure 4.17: The Upper South Esk catchment land use (2013).

The increase in Upper South Esk *Other protected* areas can be seen across higher altitude lands, particularly in the vicinity of Mt Victoria and across the sub-alpine colluvium flanks of Ben Lomond.

Recent vegetation mapping of the wider Esk Rivers basin is shown in Figures 4.18 and 4.19 and Table 4.6. This mapping is quite detailed compared to the dataset of pre-European vegetation and 1964 mapping from aerial photography. Accordingly, some classifications of vegetation were removed or merged for clarity of presentation and to assist in comparison of changes over time (4.5 below). Vegetation classes removed were saltmarsh and wetlands (14 km^2), water/sea (125 km^2), lichen lithosere (37 km^2) and sand/mud (2 km^2). Much of the water/sea coverage is a hydro-electric impoundment on the Central Plateau (upper Brumbys/Lake catchment) that displaced alpine dry sclerophyll woodland. Vegetation classes amalgamated were highland treeless vegetation (173 km^2) and moorland; sedgeland, rushland and peatland (29 km^2) were merged into *highland treeless and moorland*; wet eucalypt forest and woodland (751 km^2) were merged with rainforest (142 km^2) into the category *wet forests*.

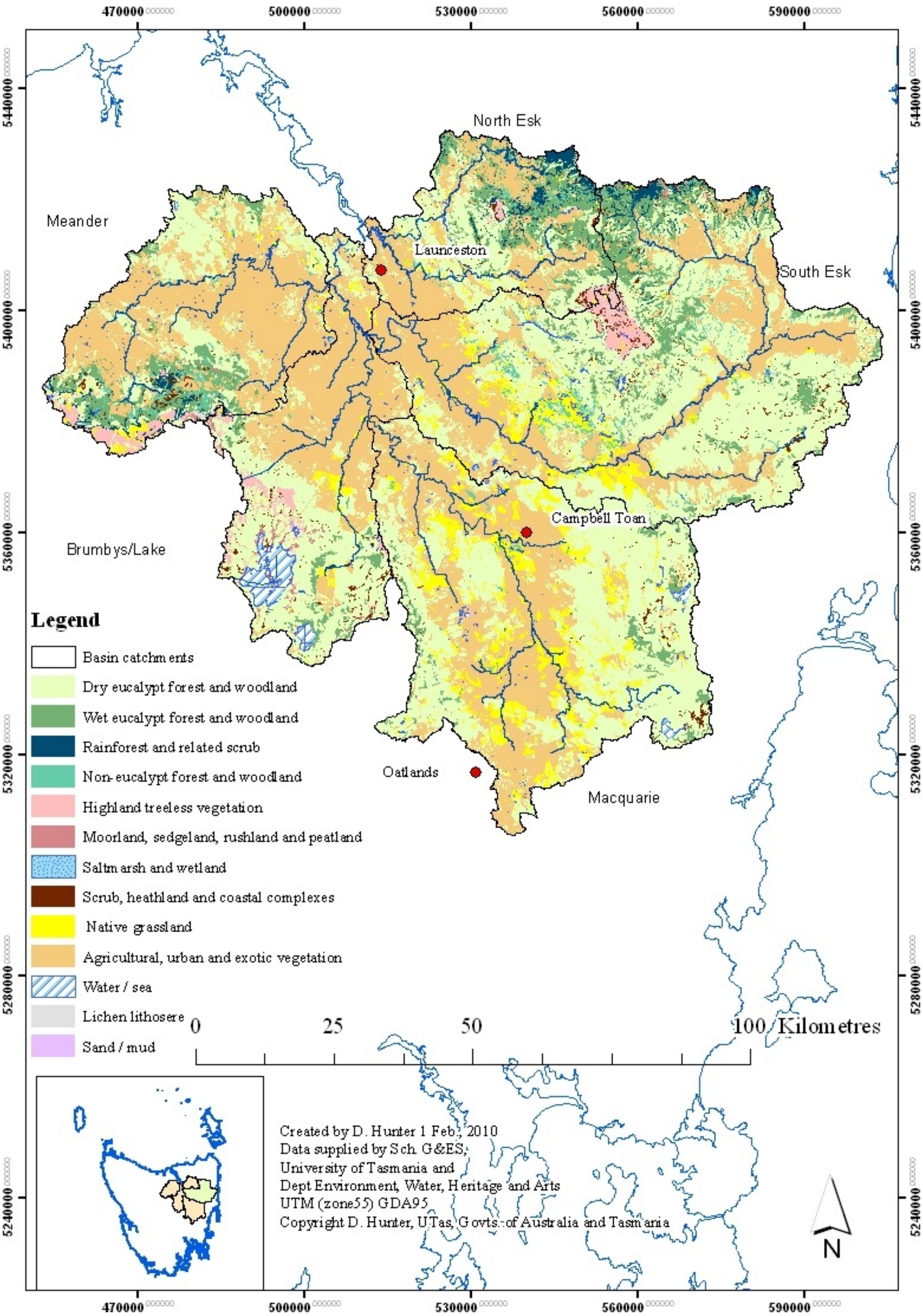


Figure 4.18: Recent vegetation of the Esk rivers basin. Source: Department of the Environment, Water, Heritage and the Arts, 2002.

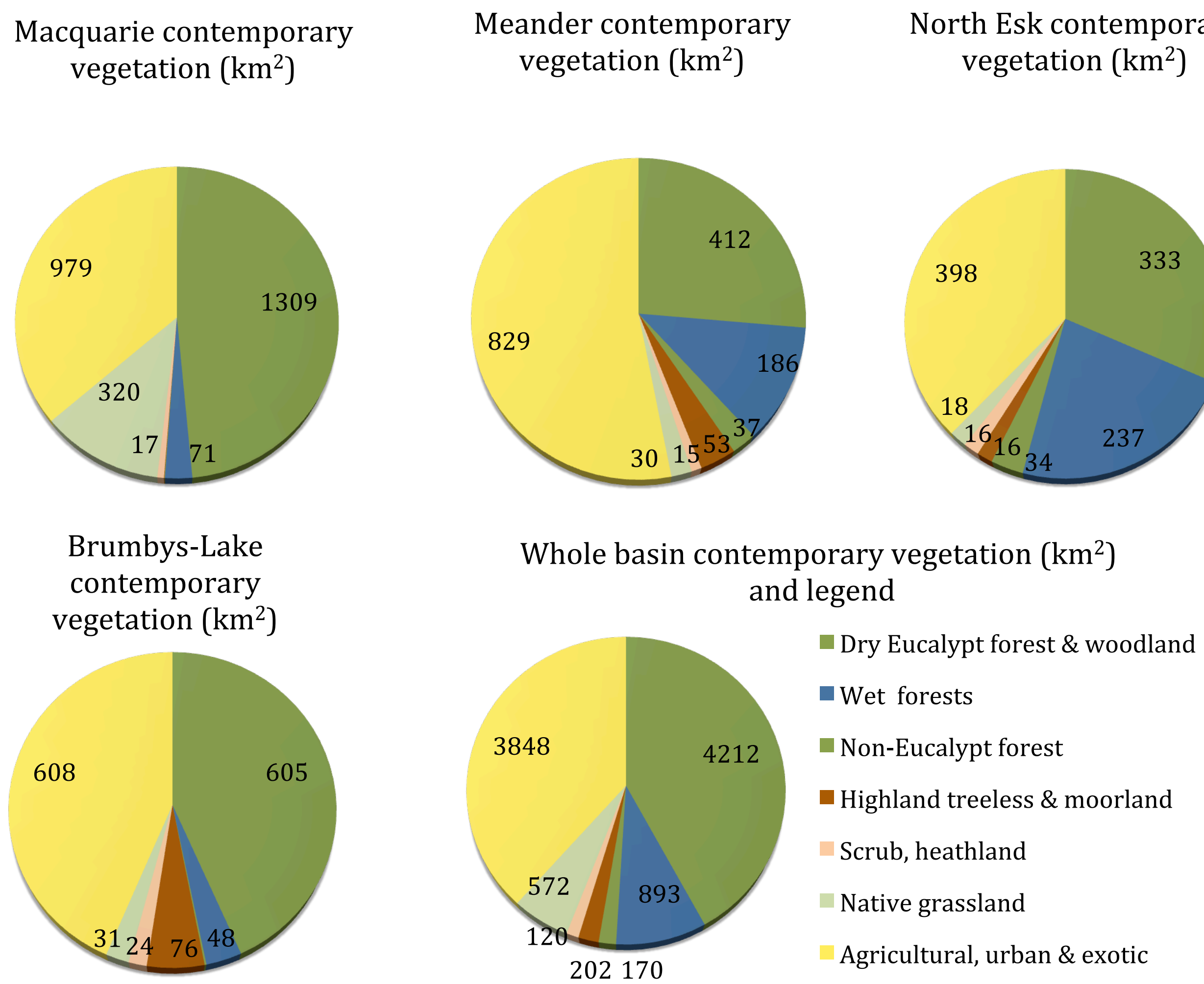


Figure 4.19: Recent vegetation of the Esk Rivers basin (km^2). Source: Dept. Environment, Water, Heritage and Arts, 2002.

These vegetation data are over a decade old and are included with interpretation of trends in mind. Forestry plantations are not shown. The originator of the data (Department of the Environment, Water, Heritage and the Arts, 2002) assigned plantations into various vegetation types, according to what original type they replaced or the adjoining forest type.

Table 4.6: Recent vegetation (2002) of the Esk Rivers basin (% catchments). Note plantations are included in the vegetation type they replaced. Source: Dept. Environment, Water, Heritage and Arts, 2002.

Catchment (%)	Macquarie	Meander	North Esk	South Esk	Brumbys-Lake	Basin
Dry eucalypt forest & woodland[a]	49	26	32	47	43	42
Wet forests[b]	3	12	22	11	3	9
Non-eucalypt forest	0	2	3	3	0	2
Highland treeless & moorland	0	3	2	2	5	2
Scrub, heathland	1	1	2	1	2	1
Native grassland	12	2	2	5	2	6
Agricultural, urban & exotic	36	53	38	31	44	38

[a]Dry eucalypt forest and woodland refers to the multi-storey structure of communities that grow in places of low effective water availability, and may grow in areas with high rainfall
[b]Combined rainforests and mixed forests (disclimax rainforest containing eucalypts and broadleaf shrubs or trees)

Comparisons of recent vegetation mapping with Pre-European (Figure 4.3) and 1964 vegetation (Figure 4.8) show substantial vegetation change in the higher rainfall and higher elevation upper catchments of the study basin over recent decades. Forestry land use has been extensive and transformative across several forest types and landscapes in these regions, where previous Aboriginal influence was minimal. Sclerophyll forests likely replaced some “mixed” forest and rainforest due to altered fire regimes and grazing practices. The expansion of land clearing, modification of native vegetation, the establishment of exotic pastures and cultivated agriculture since European occupation have markedly transformed the character of vegetation and landscapes in lower elevations. Additional areas of the Midlands and alluvial valleys of the upper North Esk and Meander catchments have been cleared for grazing and cropping since 1964. Agriculture has clearly intensified in the last decade, explaining the imperative given by NRM North to erosion control on farming land (Tamar Estuary and Esk Rivers Program, 2015).

By 2002, contemporary vegetation in the study basin was comprised of 38% agricultural, exotic and urban; native grassland 6%, dry eucalypt forests and woodlands 42% and wet and non-eucalypt forests 11% (Figure 4.18 & Table 4.6). Proportionately, the Meander and Brumbys-Lake catchments have been the most extensively developed for agriculture. They include districts close to the port of Launceston that were among the first to be intensively farmed during colonial times and districts with higher available water due to rainfall or irrigation.

The first decade of the 21st century was a time of rapid expansion of both irrigated agriculture and the plantation forestry industry across land tenures, the former expanding to 5% of the basin, mainly in the lowlands of Brumbys/Lake and Macquarie catchments (Figures 4.10 & 4.11), the latter located mostly in higher rainfall regions of northwest, northern and northeastern Tasmania and on suitable cleared/agricultural land proximal to the mills and ports (Chapter 2).

4.5 Landscape transformation over the past 200 years

A series of three snapshots of vegetation cover in the Esk Rivers basin has been presented in this chapter: pre-European occupation (<1800), mid- 20th century (1964) and contemporary land use (2001-02 & 2013) and recent vegetation mapping (2002). The transformation of the landscape over the last two centuries is visualised by area in Figure 4.20 and by percentage of the basin in Table 4.7. The attributes of various vegetation types across the datasets were incongruent, preventing standardisation of classes across the series. Therefore, to enable comparison, colour coding has been used to broadly indicate related classifications in the data presented in Figure 4.20. These are forested land, open land (including grassy woodland types) and alpine types.

The originators of the contemporary vegetation data have included plantations in the vegetation type they displaced (as noted previously). As noted previously, some minor classifications were removed from the detailed contemporary vegetation dataset for clarity and some discrepancies exist within and between the datasets due to the nature of the data.

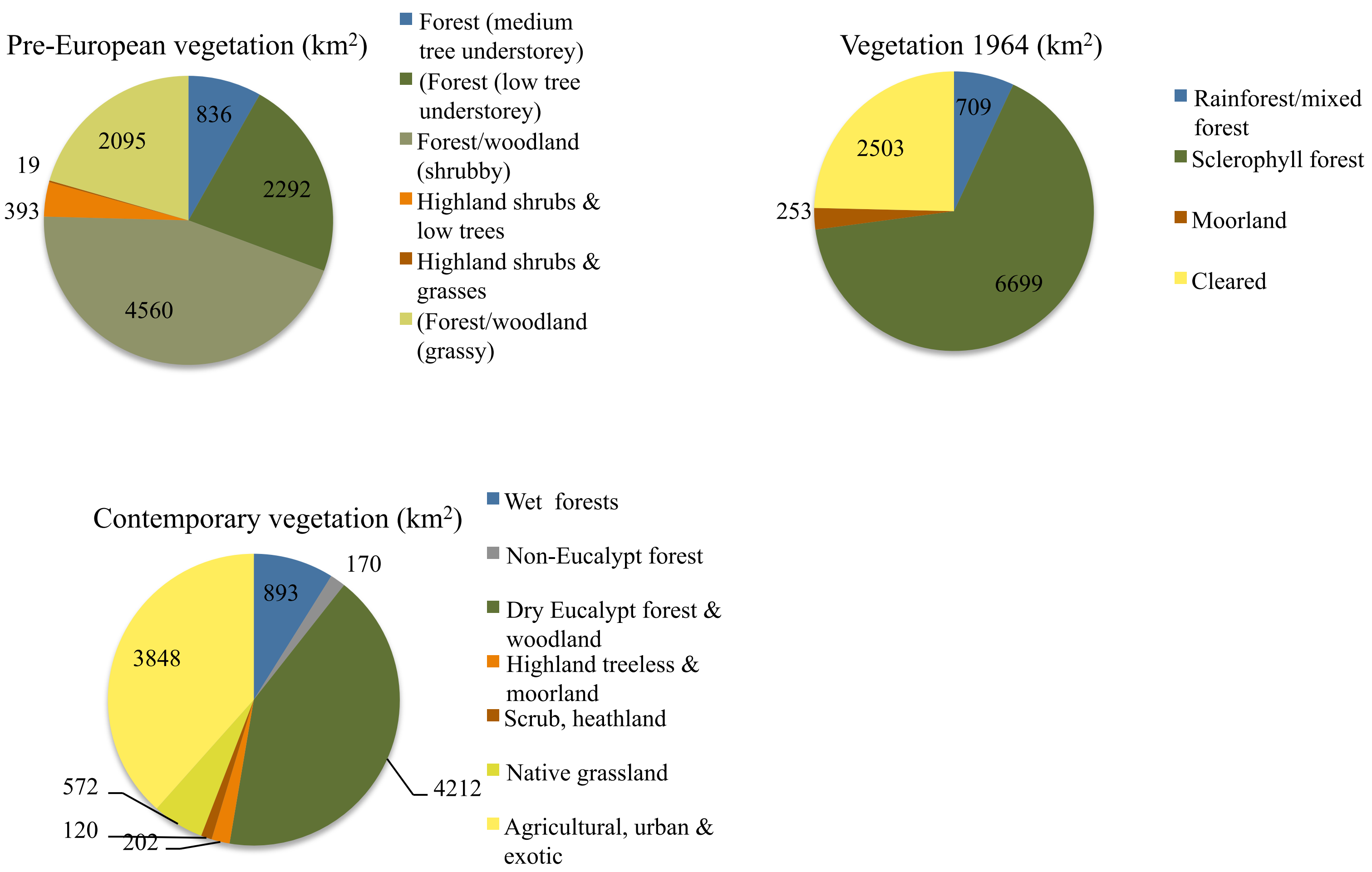


Figure 4.20: Snapshots of vegetation change in the Esk Rivers basin (km^2). Data source: Department of the Environment, Water, Heritage and the Arts, 2002; Davies, 1964, in Davies, 1965.

Table 4.7: Snapshots in time, vegetation coverage (%) in the Esk Rivers basin. sources: Department of the Environment, Water, Heritage and the Arts, 2002; Davies, 1964, in Davies, 1965.

Snap-shot	Pre-European	%	Vegetation 1964	%	Contemporary	%
Forested	Forest (medium tree understorey)	8	Rainforest/mixed forest	7	Wet forests	9
	(Forest (low tree understorey)	23	Sclerophyll forest[a]	66	Non-Eucalypt forest	2
					Dry Eucalypt forest & woodland	42
	Forest/woodland (shrubby)	45				
					Native grassland	6
Open land	(Forest/woodland (grassy)	21	Cleared	25	Agricultural, urban & exotic	38
Alpine	Highland shrubs & low trees	4	Moorland	2	Highland treeless & moorland	2
	Highland shrubs & grasses	0			Scrub, heathland	1

[a]Sclerophyll forest included woodlands.

In broad categories, coverage of forested land reduced following colonisation, most markedly since the mid-20th century. Open land (including grassy woodland types) reduced between European colonisation and the mid-20th century, then increased. Alpine vegetation types have become more open. These findings are consistent with the literature review.

Open vegetation has doubled since colonisation. Grassy ecosystems once covered about 21% of the study basin. At 1964, grassy vegetation (cleared land comprised of pastures and native grasses) covered about 25%, most of which was open savannah country before settlement. In addition, some grassy vegetation (woodland) was included in the 1964 sclerophyll classification. At 2002, native grassland covered about 6% and the agricultural, exotic and urban vegetation class covered about 38%, with open grassy or agricultural vegetation covering a total of about 44%. In addition, some grassy woodland was included in contemporary dry eucalypt types.

Rainforests, wet (mixed) forests and non-grassy sclerophyll woodlands and forests have reduced since colonisation, probably by over a third. Non-grassy forests and shrubby woodlands once covered about 76% of the basin. In 1964, all forests and woodlands covered about 73%, including some grassy woodland within sclerophyll vegetation. Contemporarily, all forests and woodlands covered about 53%, including some unquantified grassy woodlands. While the mapped extent of wet forests in the Esk Rivers basin appears to have changed little in the 2002 data from pre-European estimated extent, areas of these types of forest have been modified in structure and composition.

Changes in the distribution of vegetation types have also occurred, particularly between colonisation and 1964. While forest and woodland were cleared in some regions, there was some expansion of woodlands in the Midlands region, probably due to a change in fire regimes in the period following colonisation. The region primarily functioned as large sheep runs under absentee tenancy prior to the 1910s. These findings support earlier suggestions that the landscape equilibrium of the Midlands encountered by the colonists was partly an Aboriginal cultural landscape and partly controlled by climate, browsing and conditioned exclusion of eucalypt seedlings (Ellis, 1985; Fensham & Kirkpatrick, 1992).

The displacement of the Midlands' eucalypt forests and savannah woodlands by the contemporary vegetation class *Agricultural, urban and exotic* is particularly significant, with substantial net clearance of native vegetation evident between the 1964 and 2002 snapshots. The displacement of late Holocene native vegetation with vegetation types serving the modern community proceeded in pulses: in the first twenty years of the British colony, in the years immediately following the introduction of the Waste Lands Acts (from 1853) and again commencing 1971 with the incentive of the export woodchip industry. Extensive transformation of native forests at higher elevations has occurred and continued since 1971, while plantations for silviculture have replaced areas of both farming land and native forests, although recent replacement of lowland plantations by food production may be observed.

4.6 References

Australian Bureau of Statistics. (1910). "1301.0 - Year Book Australia, 1911." 2013, from http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/1301.01911.

BMT WBM Pty Ltd (2010). Tamar Estuary and Esk Rivers Catchment WaterCAST Model: Final Report. Brisbane, BMT Group.

Bobbi, C, Fuller, D and Oldmeadow, D (1996). South Esk Basin State of Rivers Report. Hobart, Resource Assessment Branch, Department of Primary Industry and Fisheries.

Bureau of Meteorology. (2013). "Climate data." 2013, from http://www.bom.gov.au/climate/data/.

Bureau of Meteorology. (2013). "Regional meteorological mapping." 2013, from http://www.bom.gov.au/products/.

Davies, J (1965). Landforms. Atlas of Tasmania. J. Davies. Hobart, Lands and Surveys Department.

Department of Primary Industries & Water and Department of Environment, W, Heritage and Arts, (2002). National Vegetation Information System: Tasmania- Present Native Vegetation. Canberra.

Department of Primary Industries and Water (1978-1989). Land Systems of Tasmania. Hobart.

Department of Primary Industries, P, Water and Environment (2016). Tasmanian Land Use 2013. P. Department of Primary Industries, Water and Environment. Hobart.

Department of Primary Industry, P, Water and the Environment (2013). TASVEG 3.0. T. V. M. a. M. Program. Hobart.

Department of the Environment, W, Heritage and the Arts, (2002). National Vegetation Information System- Tas- Pre-European Vegetation.

Fensham, RJ (1989). "The Pre-European Vegetation of the Midlands, Tasmania: A Floristic and Historical Analysis of Vegetation Patterns." Journal of Biogeography **16**(1): 29-45.

Forest Practices Authority (2012). State of the Forests Tasmania 2012. Hobart, Forest Practices Authority.

Green, G (2004). Plantation Forestry in Tasmania: The current resource, current processing and future opportunities, Timber Workers for Forests.

Jackson, WD and Brown, MJ (2005). Pattern and Process in the Vegetation. Vegetation of Tasmania. J. B. Reid, R. S. Hill, M. J. Brown and M. J. Hovenden. Canberra, Australian Biological Resources Study, Australian Government Department of the Environment and Heritage.

Lakin, R (1967). Primary Industry- Rural. Tasmanian Year Book No 1- 1967. R. Lakin. Hobart, Commonwealth Bureau of Census and Statistics, Tasmanian Office.

Langford, J (1965). Weather and Climate. Atlas of Tasmania. J. L. Davies. Hobart, Lands and Surveys Department.

Morgan, S (1992). Land Settlement in Early Tasmania: creating an antipodean England. Cambridge, University of Cambridge.

Pitt and Sherry and Esk Mapping and GIS Services (2012) "Potential Timber Production Estimate from the Tasmanian Private Plantation Estate."

Private Forests Tasmania (2007) "Private Property Plantations in the Landscape in Tasmania as at 31 December 2006." Information Paper No. 1.

Scott, P (1965). Land settlement. Atlas of Tasmania. J. Davies. Hobart, Lands and Surveys Department: 43-45.

Tamar Estuary and Esk Rivers Program (2015). Tamar Estuary and Esk Rivers Catchments Water Quality Improvement Plan. T. NRM North. Launceston, NRM North.

Chapter 5

Field, laboratory and statistical results and erosion hazard analysis

5.1: Soil sampling and soil physical properties verification

5.1.1 Sample site verification

Field data were examined *post hoc* for representative distribution of soil samples across simplified categories of land use within the geological classifications. In summary, the site selection and acquisition of field data largely confirmed the objective sample stratification (including relocated sites), to systematically sample the range in geology, geographic settings and land use in a manner representative of each soil type. Sampling representative of geological mapping was assured in the field by crosschecking the field map and GIS data and relocating sites as necessary. Selected geological and field data are shown in Table 5.1. The complete data are shown in Appendix 3.

Table 5.1: Selected sampling field data (1:500,000 and 1:25,000 scale geology) (continued overleaf).

Site	Geo (500k)	Geo (25k)	Catchment[a]	Sample date	Elevation (m)	EPE[b] (± m)	Land use[c]
S1.3	Qrc	Qptd	Sesk	24-Nov-10 [d, e]	915	4.3	NV
S1.4	Qrc	Qptd	Sesk	23-Nov-10	842	5.3	NVR
S1.7	Jdtm	Jd	BOD	7-Jun-11	864	4.3	NVR
S1.8	Jdtm	Jd	BOD	7-Jun-11	616	5.4	NV
S1.9	Qrc	Qptd	Sesk	27-Jul-11	724	5.6	NVR
S1.10	Qrc	Qptd	Sesk	16-Jun-11	916	5.9	NV
S1.11	Qrc	Qptd	BOD	7-Jun-11	481	3.8	NV
S1.13	Jdtm	Jd	Sesk	5-Aug-11[e]	1071	6.0	NV
S1.14	Qrc	Qptd	BOD	7-Aug-11	467	6.1	NVR
S2.1	Dgrt	Dgaap	Sesk	24-Nov-10	604	5.2	NVR
S2.2	Dgrt	Dgaap	Sesk	24-Nov-10 [e]	845	6.0	NVR
S2.3	Dgrt	Dgaap	Sesk	24-Nov-10	885	4.9	NV
S2.4	Dgrt	Dgae	Sesk	24-Nov-10 [e]	676	5.8	NVR
S2.5	Dgrh	Dgnv	Sesk	14-Jun-11	794	2.3	NV
S2.6	Dgrh	Dgnv	Sesk	22-Nov-10	842	5.1	NVR
S2.7	Dgrh	Dgnx	Sesk	22-Nov-10	827	4.1	NVR
S2.9	Dgrr	Dgne	Sesk	24-Nov-10	782	7.5	NVR
S2.10	Dgrr	Dgne	Sesk	22-Nov-10	413	5.3	NV
S2.11	Dgrr	Dgne	Sesk	14-Jun-11	802	5.3	NV
S3.4	Psp	Plb	Sesk	23-Nov-10	828	3.8	NV
S3.6	Psp	Plb	Sesk	14-Jun-11	814	5.1	NV
S3.7	Psp	Plb	Sesk	15-Jun-11	825	7.0	NV
S3.8	Psp	Pus	BOD	10-Jun-11	260	4.2	A/E
S3.9	Psp	Pfs	BOD	10-Jun-11	315	5.3	NV
S3.10	ODsm	ODq	BOD	10-Jun-11	264	6.6	A/E
S3.11	ODsm	ODqp	Sesk	7-Aug-11	295	5.0	P
S3.12	ODsm	ODq	Sesk	27-Jul-11	496	7.9	NVR
S3.13	ODsm	ODq	Sesk	23-Jun-11	597	5.5	NVR
S3.14	ODsm	ODq	Sesk	16-Jun-11	813	5.4	NV
S3.15	ODsm	ODqp	Sesk	27-Jul-11	438	6.0	P
S3.16	ODsm	ODqp	Sesk	23-Nov-10	801	5.0	NVR
S3.17	ODsm	ODqp	Sesk	23-Nov-10	370	4.3	P
S3.18	ODsm	ODqp	Sesk	23-Jun-11	551	4.5	NVR
S3.19	ODsm	ODqm	Sesk	5-Aug-11	491	7.0	P
S3.20	ODsm	ODqm	Sesk	28-Jul-11	646	3.6	NVR
S3.21	ODsm	ODqm	BOD	7-Jun-11	439	4.1	NVR
S3.22	ODsm	ODqm	Sesk	28-Jul-11	614	7.1	NV
S3.23	ODsm	ODqm	Sesk	24-Nov-10	817	6.2	NVR
S3.26	Psp	Pfs	Sesk	5-Aug-11 [e]	654	4.2	NVR

[a]Sesk: upper South Esk sub-catchment; BOD: Break O'Day catchment [b]Estimated positional error
[c]NV: native vegetation; NVR: native regeneration; A/E: agriculture/exotic vegetation; P: plantation
[d]Resampled 14/06/2011 [e]Resampled 11/10/2011

Table 5.1: Selected sampling field data (1:500,000 and 1:25,000 scale geology) (continued).

Site	Geo (500k)	Geo (25k)	Catchment[a]	Sample date	Elevation (m)	EPE[b] (± m)	Land use[c]
S4.3	Qa	Qha	Sesk	22-Nov-10	362	5.2	A/E
S4.4	Qa	Qha	Sesk	22-Nov-10	335	4.5	A/E
S4.5	Qa	Qha	Sesk	16-Jun-11	290	4.3	P
S4.6	Qa	Qha	Sesk	9-Nov-11	226	3.4	A/E
S4.7	Qa	Qha	Sesk	28-Jul-11	268	5.4	P
S4.8	Qa	Qha	Sesk	9-Nov-11	250	4.9	P
S4.9	Qrc	Qha	BOD	10-Jun-11	258	2.8	A/E
S4.11	Qrc	Qha	BOD	10-Jun-11	258	3.2	A/E
S4.12	Qrc	Qha	BOD	31-May-11	248	4.1	A/E
S4.13	Qa	Qpao	Sesk	22-Nov-10	370	5.9	NV
S4.14	Qa	Qpao	BOD	31-May-11	273	3.9	A/E
S4.15	Qa	Qpao	Sesk	9-Nov-11	271	7.1	NVR
S4.16	Qa	Qpao	Sesk	23-Jun-11	312	4.2	NV
S4.18	Qa	Qpao	BOD	9-Nov-11	243	3.8	A/E
S4.19	Qa	Qpao	BOD	31-May-11	249	4.9	A/E

[a]Sesk: upper South Esk sub-catchment; BOD: Break O'Day catchment [b]Estimated positional error
[c]NV: native vegetation; NVR: native regeneration; A/E: agriculture/exotic vegetation; P: plantation

The nine soil type 1 (basic igneous parent material) sample sites were distributed on hill and mountain land forms between 467 m and 1,071 m in elevation. Estimated mean annual rainfall ranges from 750 mm to 2000 mm (based on land systems data). There were five sample sites in the upper South Esk sub-catchment (842 m to 1,071 m elevation), and four in the Break O'Day (467 m to 864 m). Native vegetation occupied five sites, with native vegetation regeneration on the remaining four sites.

The ten soil type 2 (acid igneous parent material) sample sites were distributed on hills between 604-885 m in elevation, excepting one site at 413 m. Estimated mean annual rainfall ranges from 1,250 mm to 1,500 mm. All 10 sample sites were in the upper South Esk sub-catchment, since there were no targeted acid igneous geological units in the Break O'Day catchment. There was native vegetation on four sites, with native vegetation regeneration on the remaining six sites. Soil type 2 was the most physiographically homogeneous classification.

The twenty soil type 3 (sedimentary rock parent material) sample sites were distributed on undulating, low or high hills between 260 m and 828 m in elevation. Estimated mean annual rainfall ranges from 750 mm to 1,500 mm. There were 16 sample sites in the upper South Esk sub-catchment (295 m to 828 m elevation) and four in the Break O'Day (260 m to 439 m). There was native vegetation on six sites, with native vegetation regeneration on eight sites, forestry plantations on four sites and agriculture/exotic vegetation on the remaining two sites.

The fifteen soil type 4 (Quaternary sediments parent material) sample sites were distributed on undulating land and two hill sites between 243 m and 370 m in elevation. Estimated mean annual rainfall ranges from 625 mm to 1,500 mm. There were nine sample sites in the upper South Esk sub-catchment (226 m to 370 m) and six in the Break O'Day (243 m to 273 m). There was native vegetation on two sites, with native vegetation regeneration on one site, forestry plantations on three sites and agriculture/exotic vegetation on the remaining nine sites. This was the most physiographically complex soil classification.

Soil types 1 and 3 had the greatest altitude range, while soil type 4 had the greatest climatic range since it extends from broad, undulating alluvial plains into a high rainfall region of narrowing, steep-sided river valleys. The geological units comprising soil type 2 (acid igneous parent materials) showed widespread geographic distribution across the upper South Esk catchment but relatively low physiographic variability. Those in the far east Break O'Day catchment of the study area were minor in areal coverage and not sampled. While type 2 soils not sampled in the far northeast were of more substantial coverage, they were too remote to access and occupied similar geographic settings to soils of the main outcrops sampled in the northwest.

Land use across the study catchment was found to be in a dynamic state of change, and the digital data available (Australian Bureau of Rural Sciences, 2006) was neither up to date nor at sufficient resolution for the present application. Hence it may only be inferred from the field evidence that land use across the study catchment was probably representatively sampled. Greater reconnaissance effort would be necessary to quantify land use proportions for definitive confirmation.

According to field evidence (Table 5.1), soil types 1 and 2 (basic and acid igneous parent materials respectively) supported solely native vegetation and native regeneration following forestry. Forestry activities were found on the majority of sample sites across soil types 2 and 3 (acid igneous and sedimentary rocks parent material respectively), including forestry plantations on soil type 3 (sedimentary rocks parent material). Plantations were only sampled on soil types 3 and 4 (Quaternary sediments). Plantations were not encountered in the Break O'Day catchment during soil sampling (from November 2010 to November 2011), and may also have been absent at the time over 500 m elevation and on igneous substrates. Agriculture was confined to the Quaternary sediments of soil type 4 (excepting two of the 20 sites on soil type 3 (sedimentary rocks parent material), notably across the undulating alluvial plains and terraces of the broad Break O'Day valley and the region at the confluence of the two rivers. Outside this principal farming district, soil type 4 (Quaternary sediments) showed a mosaic of the four broad land use types.

Overall, the land use on sample sites of the upper South Esk sub-catchment was dominated by native regeneration (16 sites) and native vegetation (14 sites) followed by plantations (7 sites) and agriculture/exotic (3 sites). In the Break O'Day catchment, sites sampled were dominated by agriculture (8 sites), followed by native vegetation and native regeneration (3 sites each).

5.1.2 Vegetation communities of the sample sites

The vegetation field data and photography of each sample site were compared with the GIS *TasVeg* data. Land systems attributes were considered for accuracy.

The vegetation communities of the catchment were grouped into several types in the digital data: dry eucalypt forest and woodland; wet eucalypt forest and woodland; non-eucalypt forest and woodland; native grassland, moorland, sedgeland, rushland and peatland; rainforest and related scrub; and agricultural, urban and exotic vegetation. Small representations of non-vegetated mapped units within the group "other natural environments" (saltmarsh and wetlands, water/sea, lichen lithosere and sand/mud) were ignored. The areal extent of these communities is quantified in Table 5.2 together with the sampling density and distribution, comparing the digital data for respective vegetation communities with observations recorded in the field during sampling. The identities of communities in a state of regeneration without recognisable structure were confirmed by observation of adjoining or remnant stands.

Table 5.2: Principal vegetation communities of the study catchment by areal coverage and comparison of GIS vegetation data and field observations.

GIS community (*TasVeg* digital mapping)	Area (km^2)	Sample sites (n)	GIS data compared with field evidence
1. Sampled in study catchment (n=19 principal communities of total 85)			
Dry *Eucalyptus amygdalina* coastal forest and woodland	13	2	Confirmed
Dry *Eucalyptus amygdalina* forest and woodland on dolerite	14	1	Confirmed (regenerating)
Dry *Eucalyptus amygdalina* forest and woodland on mudstone	118	5	3 sites confirmed (2 regenerating); 1 site *E. amygdalina* on dolerite colluvium; 1 site *E. amygdalina* on older Quaternary terraces
Dry *Eucalyptus delegatensis* forest and woodland	97	5	Confirmed (2 regenerating)
Dry *Eucalyptus rodwayi* forest and woodland	2	1	Confirmed
Dry *Eucalyptus sieberi* forest and woodland not on granite substrates	60	2	Confirmed (both regenerating)
Agricultural land	172	14	11 confirmed (1 remnant native riparian vegetation on farm); 3 sites eucalypt plantation
Plantations for silviculture	129	4	Confirmed (3 eucalypt; 1 pine)
Unverified plantations for silviculture	43	2	1 site diverse native forest; 1 site thinned diverse forest
Extra-urban miscellaneous	1	1	Poor native forest regrowth
Highland *Poa* grassland	1	1	Alpine *Poa* grassland and *Leptospermum* scrub
Eastern buttongrass moorland	4	1	Confirmed
Leptospermum forest	5	1	Confirmed
Wet *Eucalyptus dalrympleana* forest	14	4	Confirmed (3 regenerating)
Wet *Eucalyptus delegatensis* forest with broadleaf shrubs	64	3	Confirmed (1 regenerating)
Wet *Eucalyptus delegatensis* forest over Leptospermum	18	1	Confirmed (regenerating)
Wet *Eucalyptus delegatensis* over rainforest	31	1	Confirmed (regenerating)
Wet *Eucalyptus obliqua* forest with broadleaf shrubs	41	4	Confirmed (regenerating)
Wet *Eucalyptus regnans* forest	15	1	Confirmed (regenerating)
Total, sampled communities	848	54	*Area: 83% of study catchment*
2. Other: not sampled in study catchment (n=4 principal communities of 66 total)			
Eucalyptus obliqua dry forest	35	0	N/A
Dry *Eucalyptus sieberi* forest and woodland on granite	15	0	N/A
Acacia dealbata forest	16	0	N/A
Nothofagus rainforest undifferentiated	36	0	N/A
Sum (major communities not sampled)	102		*Area: 10% of study catchment*
Total area[1] (n=23 of total 85)	950		*Area[1]: 93% of study catchment*

[1]Non-vegetated "other natural environments" and minor vegetation communities were ignored.

Of a total of 160 *TasVeg* vegetation communities mapped and recorded across Tasmania, 85 were represented in the study catchment. Of these, 23 principal communities accounted for 93% of the land area of the study catchment, of which 19 were represented in soil sampling of the four geological sources. The remaining four principal communities were too remote to access. It was found that the vegetation communities represented in sampling covered 83% of the area of the study catchment area. Representation of vegetation communities was therefore regarded as adequate, given the practical constraints of access to sampling sites. The greatest anomaly in sampling distribution was an underrepresentation of plantations, apparent from field observations.

Soil type 1 (soils derived from basic igneous geology) vegetation communities regenerating after forestry activity were wet *Eucalyptus delegatensis* forest over *Leptospermum*, dry *E. delegatensis* forest and woodland, wet *E. obliqua* forest with broadleaf shrubs and dry *E. amygdalina* forest and woodland on dolerite. Vegetation communities observed in the field confirmed occurrences of four different forest or woodland communities as digitally mapped, with dry *Eucalyptus delegatensis* forest and woodland occupying two of the five sites. One site was incorrectly mapped as dry *E. delegatensis* forest and woodland on mudstone. The site was actually on dolerite colluvium.

Soil type 2 (soils derived from acid igneous geology) vegetation communities regenerating after forestry activity were wet *Eucalyptus delegatensis* over rainforest (mixed forest), wet *E. obliqua* forest with broadleaf understorey and wet *E. dalrympleana* forest. Vegetation communities observed in the field were largely consistent with the GIS data. Inconsistencies were few and generally minor at sub-community level. Four forest or woodland communities were found as mapped on eight sites, while a site mapped as highland *Poa* grassland was found to be highland *Leptospermum* scrub and *Poa* grassland and another site mapped as “extra-urban miscellaneous” was found to be poorly structured native vegetation regeneration.

Soil type 3 (soils derived from sedimentary rocks) vegetation communities regenerating after forestry activity were dry *Eucalyptus sieberi* forest and woodland not on granite substrates, dry *E. delegatensis* forest and woodland, dry *E. amygdalina* forest and woodland on mudstone, wet *E. obliqua* forest with broadleaf shrubs, wet *E. delegatensis* forest with broadleaf shrubs and wet *E. dalrympleana* forest. Vegetation communities observed in the field were largely consistent with the GIS data. However, a high altitude site mapped as dry *E. rodwayi* forest and woodland was found to be an alpine moorland with scattered eucalypt copses, a site mapped as “unverified plantations for silviculture” was found to be biodiverse dry forest while one of the two *E. sieberi* forest sites was without community structure, quite clear of any understorey, and likely serving as a firebreak for an adjacent *Pinus radiata* plantation. Three native vegetation communities above 800 m elevation consisted of non-eucalypt vegetation (moorland, grassland/scrub and *Leptospermum* forest).

Soil type 4 (soils derived from Quaternary sediments) vegetation communities were observed in the field to be the least consistent with the GIS data, given the complexity of the vegetation mosaic in this source coupled with inaccuracy at the nominal 1:100,000 mapping scale and recent land use changes. The one site regenerating after forestry activity was incorrectly mapped as dry *E. amygdalina* forest and woodland on mudstone (sedimentary rocks), whereas the site was on a Quaternary river terrace, according to the topography. Further, three of the 12 targeted sites mapped as agricultural land had undergone conversion to forestry plantations, while another was in remnant riparian vegetation adjacent to agricultural land. The site mapped as "unverified plantations for silviculture" was in fact thinned but biodiverse dry forest.

On the whole, the *TasVeg* mapping of vegetation communities within the study area was found to be largely consistent with the field evidence, allowing for limitations in accuracy due to the nominal 1:100,000 mapping scale. Mapping of forestry plantations caused the greatest number of inconsistencies, where two forest sites were wrongly mapped as unverified plantations and three sites mapped as agricultural vegetation had recently been converted to plantation land use.

5.1.3 Physical characteristics of soils of the sample sites

The physical characteristics of the soils and soil profiles of each sample site and of each geological classification were collated and examined. The soil profile descriptions and photography were compared within and between soil types. Land systems attributes were considered for accuracy of mapped attributes compared with site observations to confirm target site attributes.

Type 1 soils of basic igneous parent materials were typically gradational or weakly duplex in texture. Some soils had a shallow (0-4 cm) O horizon or humus layer; the A horizons were 10-13 cm deep. Generally these dark, organic-rich, loamy soils formed in pockets between dolerite stones and graded into orange-brown clayey subsoil with a total profile depth of 17-45 cm. Only one eluviated (E) horizon between horizons A and B was identified (S1.7). Land systems codes were entirely consistent with site attributes.

Type 2 soils of acid igneous parent materials were typically gradational or weakly duplex in texture, with sand or grit (>2 mm diameter) throughout. O horizons were absent. A horizons of mid to dark brown or greyish sandy/gritty loam were formed to 8-20 cm depth, followed by B horizons of generally paler silty sand, with clay near the regolith, to 21-48 cm depth. One soil profile (S2.10) had an eluvial E horizon. Land systems codes were once more entirely consistent with site attributes.

Type 3 soils of sedimentary rocks parent materials varied from gradational to strongly duplex in texture; one was possibly uniform (S3.13). Only one soil had a clear O horizon 0-2 cm (S3.7). A horizons of ODsm soils were generally dark brown silty or loamy to 3-18 cm depth. A horizons of Psp soils were generally grey-brown to black peaty or loamy to 2-18 cm depth. B horizons of ODsm soils ranged from pale, mid or dark yellow, orange, brown or grey clay or loamy clay to 18-50 cm depth. B horizons of Psp type soils ranged from mottled orange-grey to grey-brown gritty silt to heavy clay to 23-48 cm depth. B horizons of overall type 3 soils were stony. ODsm soils were generally stonier and paler than Psp soils. Land systems data (code third digit, Appendix 3) distinguished sedimentary rock subsets of siliceous (sand/quartz based sediments) and argillaceous (clay-based sediments). According to land systems mapping, ODsm soils were derived almost equally from both subsets, while Psp soils were entirely argillaceous. From the soil descriptions, most Psp soils conformed to the expected sedimentary rock subset and most ODsm soils conformed to the mapped proportion of both subsets. Land systems attributes were fairly consistent with the field observations.

Type 4 soils of Quaternary sediments were generally gradational in texture; some older alluvial terrace soils were weakly duplex. The six pastoral soils had turf sods; several continued deeper than practicable to dig by hand. The A horizons ranged from mid to dark grey, grey-brown or reddish-brown silty or sandy loam to 2-28 cm depth. The B horizons were paler and sandy, with greater clay content and often with coarse sand or small stones low in the profile, down to 25-55 cm depth. Four soils had two B horizons (B1 and B2), grading into gritty or stony compacted clay. Two soils had an eluvial E horizon (S4.14 and S4.19). The two upstream sites had sandier soil, consistent with a greater proportion of soil type 2 (acid igneous) weathering products, while agricultural and plantation soils tended to be more compacted and heavier than soils under native vegetation or regeneration. Land systems codes (third digit) were almost entirely consistent, with all but one sample site mapped as either siliceous or argillaceous geology/sediment. From field evidence, one site (S4.13), consistent with an old Quaternary river terrace high in the catchment below granite (acid igneous) outcroppings, was indeed derived from acid igneous origins consistent with its Land Systems code according to later statistical analysis (5.3.2).

In summary, soil type 1 had organic-rich loamy topsoils to clayey subsoils. Type 2 soils generally lacked humus and had gritty, sandy profiles with some clay near the base of the subsoils. Type 3 soils were more variable than the other soils, but had increasing clay content with depth and were quite stony throughout. Type 4 soils tended to have silty or sandy loam topsoils and gritty or stony clay based subsoils. Soil types 1, 2 and

4 had distinctive and generally consistent soils, even though soil type 1 soils had considerable range in topographic and climatic settings. Soils of type 3 (sedimentary rock parent materials) were generally more variable in profile and textures, including between soils of ODsm and Psp geological units. However, soil type 3 occupied half the area of the study catchment. Over this extent and altitudinal range, the sedimentary rock strata characteristics and topographic and climatic conditions were variable. Nevertheless, it was found that the soils of each geological classification had distinctive physical characteristics, supporting the geological basis for soil type classification and accuracy of soil mapping. Land systems proved a useful tool to the project, before and after sampling.

5.1.4 Discussion, soils field work verification

Differences in physical soil characteristics were confirmed between the four primary geological sources, although the soils of the source of greatest extent, sedimentary rock parent materials (soil type 3), were more variable. Overall, the soils data validated *a priori* classification by geological sources.

The soil sampling of 54 sites across the study catchment accounted for all major geological units (Tables 3.1 and 3.2) and 19 of the 23 major vegetation communities, including a range of land uses (Tables 5.1 and 5.2). The range in altitudinal, climatic and other geographic settings associated with each of the soil types was well represented.

Currency of available land use data at the time of sampling was problematic because of contemporary changes in land use and some digitised source data dating back to 1996 (Appendix 1). Nevertheless, sampling across simplified land use categories was found adequate *post hoc*. Native vegetation was found on 18 sites, native vegetation regeneration on 18 sites, agricultural/exotic vegetation on 11 sites and plantations for silviculture were found on seven sites. It was found that the sampling distribution adequately represented the range of land uses, with the possible exception of plantations.

Although comparisons of vegetation community field evidence with digital mapping found some inconsistencies, they were few and generally minor at sub-community level. The digital vegetation data were current at the times of sampling. Field evidence differed from the described (mapped) communities for a small number of sites while others were inaccurate due to inadequate resolution of source data at the mapped scale. The vegetation communities sampled represented a nominal 83% of the study catchment area. Of 14 sites mapped as agricultural, three had since been converted to plantation, while the two sites mapped as unverified plantations were found to be native vegetation. The mapped highland *Poa* site was found to be *Leptospermum* and *Poa* vegetation, while the *extra-urban miscellaneous* site was found to be regenerating to native forest.

Substantial physiographical complexity was encountered in consideration of the sampling strategy. However, it is considered the desk-top based spatial design of this study and selection of sample sites have been validated *post-hoc*, providing a suite of soil samples that are both distinctive and representative of the geological units for the purpose of chemical analysis and subsequent identification of a fingerprint discriminatory of the four soil types (5.3.2).

5.2 Laboratory results

5.2.1 Weight loss on ignition (LOI)

Determinations were made for both % organic matter and % CO_3^{2-} content of the mineral fraction, with greatest interest being in the organic component.

Oven position error ranged from RSD=7-30%, excluding an outlier of RSD=57%. Reproducibility measured across 8 triplicate samples was RSD=0.7-8.1%. Reproducibility of organic content assay both within and between batches was RSD=1-8%, excluding one outlier of 16%.

Summary results of the organic assays are shown in Figures 5.1 and 5.2. Mean inorganic determinations for the soil types were 1.68 % (soil type 1), 1.76 % (soil type 2), 0.751% (soil type 3) and 0.851% (soil type 4), showing similarities between the two igneous soil types and between the two sedimentary soil types. Complete LOI data are shown in Appendix 9.

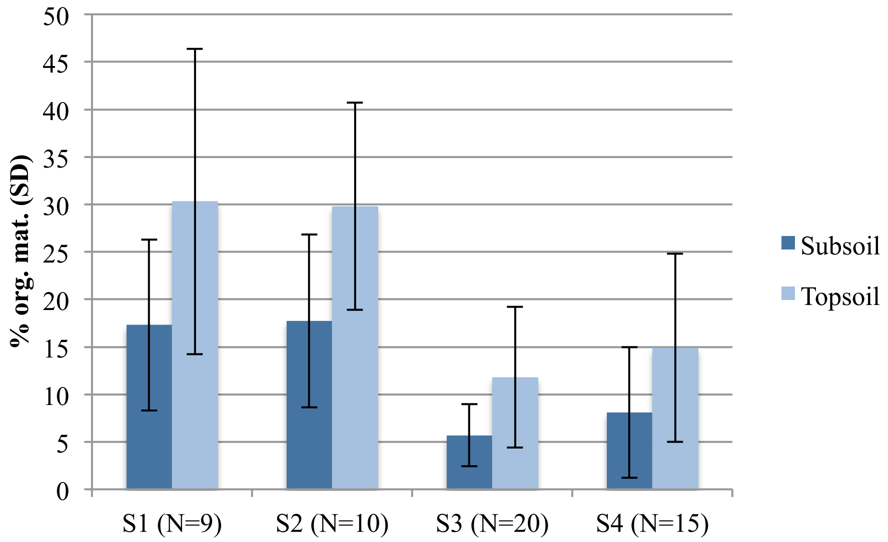


Figure 5.1: Organic matter by soil types: subsoil and topsoil (% dry weight by LOI).

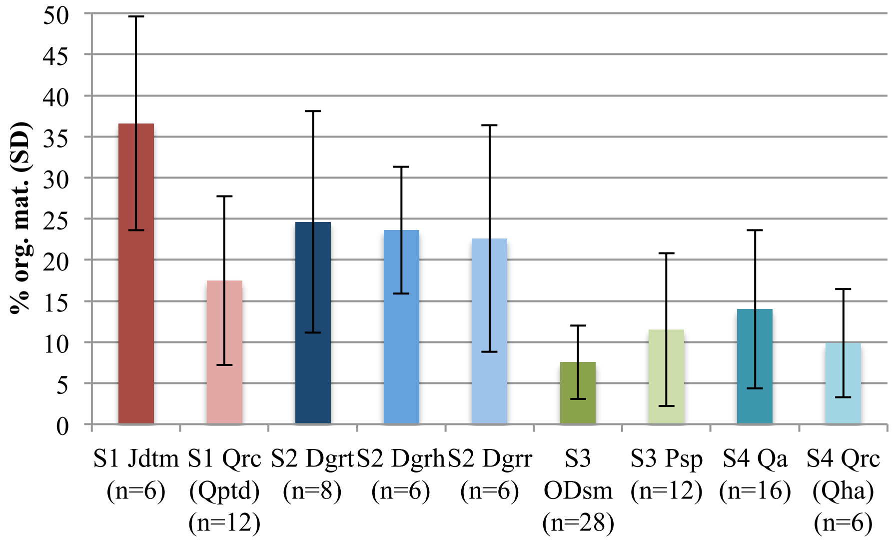


Figure 5.2: Organic matter by sub-categories of soil types: combined sub- and topsoil (% dry weight by LOI).

Topsoils were higher in % organic content than subsoils. Soils from regrowth forest sites were generally higher in organic content than other land uses, although the highland moor topsoil (peat) organic content was 36% (soil type 3, Psp) and an alpine dolerite site topsoil 59% (soil type 1, Jdtm). Overall, alpine dolerite soils of soil type 1 had the highest organic content. The soils were typically located in fire-protected hollows between prominences in dolerite outcrops or talus/colluvium. However, the topographically exposed sub-alpine scree soils of Quaternary colluvium derived from Jurassic dolerite (Qptd) were relatively low in organic content.

The second highest organic content was found in type 2 soils, the acid igneous soils. Lower organic content values were expected for these relatively climatically exposed topsoils. Almost all these soils were quite sandy or gritty in texture and located on upper slopes in dry sclerophyll or regrowth forests (Appendix 3).

The sub-category ODsm of soil type 3, occupying the mid-altitudes of the catchment across steeply incised profiles of the landscape, had the lowest organic content (subsoil 5.7% and topsoil 11.8%).

5.2.2 Sample fractionation

Sample weights (air-dried) were recorded in three fractions during recovery of the <63 μm fraction for acid digestion. The samples air-dried to a mean bulk weight of 463.9 g (N=108), of which the mean obtained finer fraction (<63 μm) was 23.6 g (5.1%), ranging from 0.6-105.7 g (0.1-10.1%). Repeat sampling of several lower yielding samples was necessary to obtain sufficient fines for analyses. Selected results are shown in Table 5.3 and Figures 5.3, 5.4 and 5.5.

Table 5.3: Fractionation of air-dried soils (mean % dry wt. soil type).

Soil depth	Subsoil			Topsoil		
Soil fraction (% soil wt.)	>2 mm	≤2 mm, >63 µm	≤63 µm	>2 mm	≤2 mm, >63 µm	≤63 µm
S1 Basic igneous (n=9)	50	47	2.5	39	57	3.4
S2 Acid igneous (n=10)	34	63	3.6	35	61	3.9
S3 Sedimentary (n=20)	39	55	5.4	34	60	6.7
S4 Quaternary sediments (n=15)	34	59	6.1	24	68	8.0

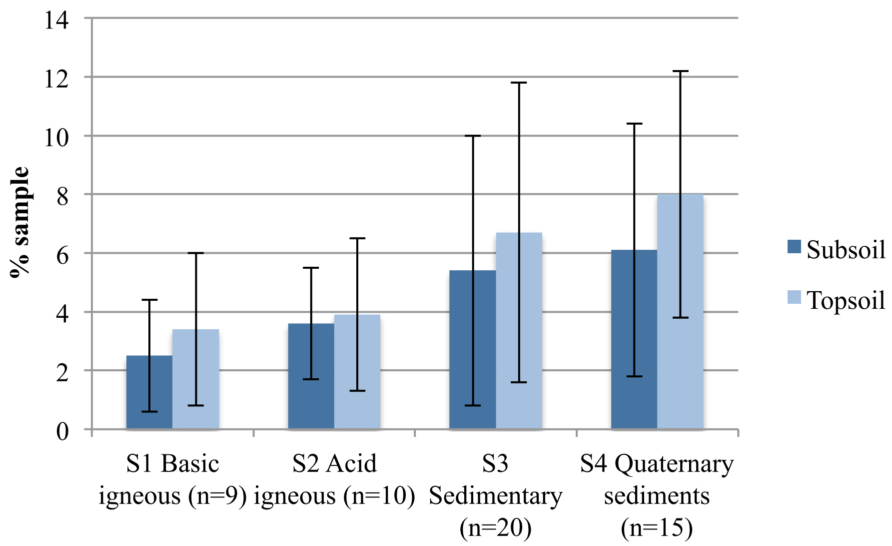


Figure 5.3: Fine fraction (<63 µm) in sub- and topsoils of soil types by mean percentage dry wt. (SD).

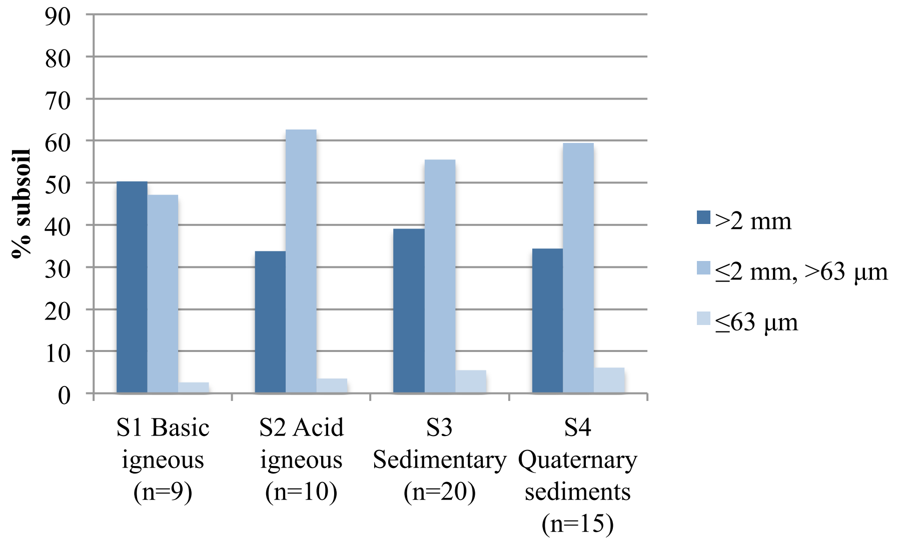


Figure 5.4: Fractionation of subsoils by mean percentage dry weight.

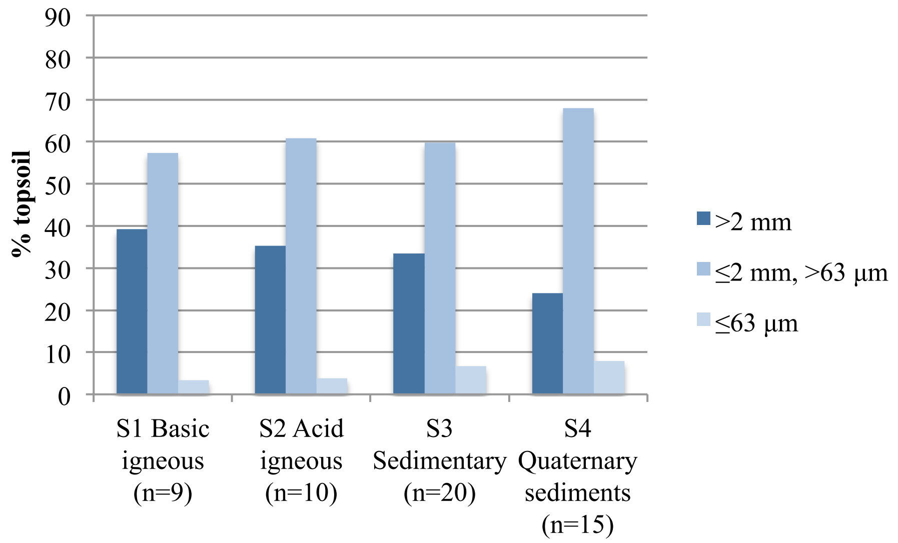


Figure 5.5: Fractionation of topsoils by mean percentage dry weight.

The igneous soil types, highest in altitude in the dry sclerophyll forests of the upper South Esk catchment, had lowest yields of the finer fraction. Soil type 3 had fines values not far below those of soil type 4, valley alluvium. From the data, the greatest potential source of suspended sediment if eroded is found in soil type 3 that covers 50% of the catchment across the mid-slopes. Nevertheless, among the type 2 soils were several structureless profiles that would likely be of higher erosivity upon disturbance (Appendix 3). The vulnerability of soil type 4 under intensive agricultural activities to stream bank erosion is well known (Chapter 2).

5.2.3 Assessment of analytical reproducibility

To assess accuracy of the analytical methods, the recovery of elements in SRMs following ICP-MS analysis of the acid-digested soils was compared to published values. From the results (Table 5.4 below; Appendix 6), ignoring elements not detected by this method (ND; <LOQ), recovery across total SRM replicates and batches was generally in good agreement with published values for basalt BHVO2 (85-106%, excepting outliers Cd, Sn, Sb and Cs) and in moderate to good agreement for Montana soil NIST2711a (55-98%, except La and Hf).

Recovery results for granite SRM AC-E were in moderate to good agreement for Fe, the high field strength elements (HFSE) as well as several trace elements (74-129%) but poor for a number of other elements, notably rare earth elements (REE; 12-23%) and Al (32%). The particularly high measured value for Sc (1243% recovery; RSD=8%) in AC-E using ICP-MS based methods was consistent with literature values (Yu *et al.,* 2001), in comparison to values found using x-ray fluorescence (XRF) or instrumental neutron activation analysis (INAA) which support the suggested consensus value (Max Planck Institute, 2012: Appendix 6b addendum). The low recovery of Al and REE in AC-E may have been associated with incomplete acid attack on some refractory REEbearing grains, consistent with known challenges in digestion of granite rock samples (for example Taylor *et al*., 2002). However, concerns for incomplete recovery of HFSE in resistant grains of the granite SRM (Yu *et al.*, 2000; Bowie *et al.*, 2010) using the open vial digestion method were unfounded, with HFSE recovery values of 86-101%, the highest value being for recovery of Ti (see 3.3.3).

While a visible suspension and/or undissolved sample was evident in most of the prepared digestions prior to ICP-MS analysis, the priority objective was considered the achievement of reproducible results leading to a statistically robust fingerprint, with or without complete digestion.

Table 5.4: SRMs published[a] and measured concentrations (mg/kg) and recovery (%). Values shown as "<…" indicate the measurements were <LOQ, not detected (ND).

Sample	BHVO2[b] (N=9)			AC-E[c] (N=9)			NIST2711a[d] (N=11)		
mg/kg	Publ.	Meas.	Rec (%)	Publ.	Meas.	Rec (%)	Publ.	Meas.	Rec (%)
Al	71448	61500	86	77800	24900	32	67200	48100	72
Sc	32	28.0	88	0.11	1.37	1243	8.5	7.42	87
Ti	16300	15500	95	595	598	101	3170	2890	91
V	317	316	100	3	<0.799		80.7	76.2	94
Cr	280	282	101	3.4	<1.40		52.3	43.9	84
Mn	1317	1260	95	449	379	84	675	600	89
Fe	86300	79000	92	17350	15500	89	28200	25700	91
Co	45	44.1	98	0.2	<1.47		9.89	9.48	96
Cu	127	126	99	4	<8.83		140	132	94
Zn	103	99.2	96	224	225	101	414	374	90
Rb	9.11	8.37	92	152	101	66	120	65.7	55
Sr	396	377	95	3	<2.29		242	174	72
Y	26	22.2	85	184	21.3	12		17.4	
Zr	172	163	95	780	757	97		105	
Nb	18.1	17.1	95	110	94.6	86		17.9	
Mo	4	<7.08		2.5	<7.08			<7.08	
Cd	0.06	<0.280		0.61	0.735	121	54.1	50.4	93
Sn	1.7	2.09	123	13	15.1	116		4.40	
Sb	0.13	<0.252		0.4	0.320	80	23.8	23.4	98
Cs	0.1	<0.349		3	1.85	62	6.7	4.79	71
Ba	131	127	97	55	40.6	74	730	647	89
La	15.2	14.8	97	59	9.44	16	38	17.8	47
Ce	37.5	36.8	98	154	35.5	23	70	38.5	55
Pr	5.35	5.03	94	22.2	3.85	17		4.76	
Nd	24.5	23.3	95	92	16.3	18	29	18.7	64
Sm	6.07	5.78	95	24.2	4.13	17	5.93	3.85	65
Eu	2.07	1.94	94	2	0.285	14	1.1	0.666	61
Gd	6.24	5.38	86	26	3.58	14	5	3.19	64
Tb	0.92	0.882	96	4.8	0.739	15	0.8	0.547	68
Dy	5.31	5.03	95	29	4.98	17	5	3.50	70
Ho	0.98	0.924	94	6.5	1.04	16		0.694	
Er	2.54	2.39	94	17.7	3.18	18		2.08	
Tm	0.33	0.292	88	2.6	0.507	19		0.315	
Yb	2	1.83	91	17.4	3.49	20		2.22	
Lu	0.274	0.233	85	2.45	0.474	19	0.5	0.315	63
Hf	4.36	4.44	102	27.9	26.0	93	9.2	3.44	37
Tl		<0.149		0.9	0.855	95	3	2.39	80
Pb	1.6	1.70	106	39	36.3	93	1405	1340	95
Bi		<0.657		0.4	0.152	38		1.61	
Th	1.22	1.19	98	18.5	8.46	46	15	10.7	72
U	0.403	0.427	106	4.6	4.08	89	3.01	2.45	81

Certificates of analysis:
[a]Published values in this table were amended as and if updated on the database *GeoReM* <http://georem.mpch-mainz.gwdg.de/sample_query_pref.asp> (Max Planck Institute, Version 14, 04/01/2012); [b]United States Geological Survey (1998); Jochum and Nehring (Max-Planck-Institut fuer Chemie; GeoRem, 2006); [c]Centre de recherches petrographiques et geochimiques, Centre national de la recherche scientifique (CRPG-CNRS; Govindaraju, 1987);
[d]National Institute of Standards and Technology (2009)

Excluding the few outliers, precision both within and across batches for BHVO2 was generally RSD≤12% and for NIST2711a precision was RSD≤20%. Precision for Fe and HFSE for all SRMs was RSD≤12% (recovery 86-102%), with only one exception each for precision and for accuracy. However, RSD values exceeded 30% for many AC-E elements, both within and across batches.

Environmental sample heterogeneity and reproducibility of element concentrations were considered from the precision of replicate soil samples analyses, both within and between process batches. Analyses of four soils each from Soil types 1, 2 and 4 and five soils from Soil type 3 were replicated and one soil was twice analysed in triplicate, as shown in Tables 5.5a-e below. The full data are given in Appendix 7.

Table 5.5a: Soil type 1 replicates measured elemental concentrations and precision (%RSD). Values shown as "<…" indicate the measurements were <LOQ, not detected (ND).

Sample	1.4 sub (Qrc)[a]		1.11 sub (Qrc)[b]		1.11 top (Qrc)[c]		1.7 sub (Jdtm)[d]	
	mg/kg	RSD (%)	mg/kg	RSD (%)	mg/kg	RSD (%)	mg/kg	RSD (%)
Al	31400	33	46300	5	20800	40	32300	30
Sc	11.5	20	14.6	9	5.04	27	9.33	21
Ti	4200	4	10200	2	10300	8	6260	4
V	170	1	219	2	137	5	227	4
Cr	143	2	86.7	2	50.1	4	43.4	5
Mn	697	2	636	3	1299	3	1810	4
Fe	47300	3	59300	2	38000	5	75300	1
Co	23.3	3	62.9	2	51.2	5	40.0	2
Cu	28.9	9	57.1	1	36.9	9	84.9	2
Zn	78.2	6	57.5	6	49.1	5	75.7	6
Rb	3.96	71	30.7	5	31.5	22	2.16	30
Sr	34.2	25	29.2	7	25.6	30	12.2	19
Y	3.79	61	3.00	26	1.60	46	2.20	41
Zr	155	3	231	2	253	8	117	3
Nb	9.82	2	14.4	2	15.7	11	9.32	4
Mo	<7.08		<7.08		<7.08		<7.08	
Cd	<0.280		<0.280		<0.280		<0.280	
Sn	2.97	6	1.77	1	1.60	8	1.95	15
Sb	0.388	9	<0.252		<0.252		<0.252	
Cs	2.60	41	0.601	16	0.703	43	0.569	18
Ba	134	20	280	8	340	14	94.0	5
La	4.02	79	4.31	25	2.70	28	2.75	25
Ce	10.3	70	10.9	22	6.66	31	6.52	25
Pr	1.55	83	0.884	29	0.669	24	0.721	17
Nd	5.54	63	4.42	24	2.70	28	3.10	18
Sm	1.54	80	0.83	23	0.530	43	0.683	26
Eu	0.511	151	0.165	27	7.69E-02	49	0.150	54
Gd	1.21	85	0.601	22	0.368	40	0.542	38
Tb	0.50	146	8.50E-02	39	<0.0822		0.110	60
Dy	1.52	79	0.762	25	0.431	50	0.669	41
Ho	0.515	132	0.127	25	7.61E-02	41	0.134	68
Er	0.987	86	0.478	27	0.273	42	0.418	42
Tm	0.376	161	<0.0747		<0.0747		<0.0747	
Yb	1.08	79	0.590	20	0.291	46	0.368	50
Lu	0.404	154	<0.0548		<0.0548		5.99E-02	96
Hf	4.63	2	6.41	2	7.07	10	3.41	4
Tl	0.268	42	0.483	3	0.524	28	0.149	49
Pb	14.1	2	12.8	3	17.3	8	11.7	2
Bi	0.261	69	<0.657		<0.657		<0.657	
Th	4.01	35	4.00	12	2.30	20	1.81	16
U	2.06	5	1.76	5	1.69	4	1.52	1

[a]Represents n=4; Batch 1 (1), Batch 4 (triplicate)
[b]Represents n=3; Batch 1 (triplicate)
[c]Represents n=4; Batch 1 (1), Batch 4 (triplicate)
[d]Represents n=4; Batch 1 (1), Batch 4 (triplicate)

Table 5.5b: Soil type 2 replicates measured elemental concentrations and precision (%RSD). Values shown as "<…" indicate the measurements were <LOQ, not detected (ND).

Sample	2.1 top (Dgrt)[a]		2.5 sub (Dgrh)[b]		2.5 top (Dgrh)[c]		2.11 sub (Dgrr)[d]	
	mg/kg	RSD (%)	mg/kg	RSD (%)	mg/kg	RSD (%)	mg/kg	RSD (%)
Al	38700	39	63200	27	38900	48	47300	38
Sc	2.47	23	6.77	21	3.89	28	7.08	25
Ti	3190	7	6450	4	5930	7	8390	11
V	28.6	7	95.6	2	78.0	4	123	5
Cr	9.63	7	50.5	3	31.2	3	54.2	6
Mn	124	4	295	5	246	12	788	8
Fe	16800	3	51600	3	38600	3	68300	5
Co	2.25	11	9.28	12	3.21	19	14.4	8
Cu	10.8	9	15.5	6	12.3	5	22.8	8
Zn	17.8	10	85.3	6	52.5	18	97.6	10
Rb	98.0	17	31.0	50	67.7	17	33.7	29
Sr	5.99	52	18.5	56	27.8	37	41.9	31
Y	2.40	40	3.98	62	2.86	46	2.13	41
Zr	264	2	327	5	453	6	255	9
Nb	42.9	2	29.3	6	25.0	8	27.5	6
Mo	<7.08		<7.08		<7.08		<7.08	
Cd	<0.280		<0.280		<0.280		<0.280	
Sn	14.6	5	15.7	62	8.53	10	3.88	5
Sb	<0.252		<0.252		<0.252		<0.252	
Cs	6.01	130	1.85	81	2.83	82	1.81	59
Ba	77.8	82	76.6	46	185	35	263	14
La	9.14	31	7.60	69	8.93	11	3.22	35
Ce	22.9	26	25.1	65	13.2	12	13.5	33
Pr	2.51	24	1.87	67	1.95	15	0.815	30
Nd	9.08	21	6.96	62	6.53	22	3.12	31
Sm	1.71	30	1.43	60	1.27	33	0.819	39
Eu	<0.0706		0.163	75	0.147	75	0.165	105
Gd	1.00	33	1.04	59	0.753	43	0.587	53
Tb	0.174	67	0.209	57	0.159	60	0.168	97
Dy	0.758	39	1.35	59	0.868	51	0.782	45
Ho	0.149	61	0.247	58	0.190	56	0.194	87
Er	0.436	45	0.775	54	0.560	45	0.506	54
Tm	7.81E-02	67	0.117	64	0.112	80	0.122	114
Yb	0.461	36	0.920	54	0.783	36	0.544	47
Lu	9.42E-02	61	0.127	55	0.130	52	0.130	115
Hf	8.79	2	10.2	4	13.5	5	7.43	6
Tl	1.13	34	0.893	38	0.835	18	0.580	22
Pb	31.0	32	35.7	6	34.4	10	26.9	2
Bi	1.76	14	0.962	25	0.949	33	<0.657	
Th	25.3	31	22.2	37	12.9	20	6.80	13
U	12.4	25	22.7	3	14.5	7	5.05	3

[a]Represents n=3; Batch 1 (1), Batch 4 (duplicate)
[b]Represents n=4; Batch 1 (1), Batch 4 (triplicate)
[c]Represents n=4; Batch 1 (1), Batch 4 (triplicate)
[d]Represents n=4; Batch 1 (1), Batch 4 (triplicate)

Table 5.5c: Soil type 3 replicates measured elemental concentrations and precision (%RSD). Values shown as "<…" indicate the measurements were <LOQ, not detected (ND).

Sample	3.12 top (ODsm)[a]		3.15 top (ODsm)[b]		3.22 sub (ODsm)[c]		3.9 sub (Psp)[d]		3.9 top (Psp)[e]	
	mg/kg	RSD (%)	mg/kg	RSD (%)	mg/kg	RSD (%)	mg/kg	RSD (%)	mg/kg	RSD (%)
Al	5430	17	14000	10	17000	11	25400	17	7120	6
Sc	2.06	9	3.87	15	4.3	13	4.97	15	1.39	12
Ti	2700	3	3710	12	3680	13	6620	17	2250	76
V	12.7	6	35.9	3	41.1	4	93.5	7	23.4	16
Cr	9.94	12	37.0	5	41.6	4	58.3	2	21.1	2
Mn	50.3	3	48.7	3	1190	4	70.7	4	91.2	2
Fe	1560	3	10000	2	8830	3	26700	1	6230	3
Co	<1.47		<1.47		2.15	8	4.23	3	<1.47	
Cu	<8.83		<8.83		22.0	144	<8.83		<8.83	
Zn	<8.04		12.2	11	24.7	74	13.33	6	<8.04	
Rb	15.3	3	26.0	15	46.7	15	12.55	24	21.22	5
Sr	21.8	11	13.7	14	21.4	15	9.89	56	17.1	14
Y	8.60	10	10.3	11	11.5	22	6.34	33	3.86	16
Zr	165	8	216	2	309	2	274.73	4	162.55	11
Nb	5.35	15	9.18	11	7.28	22	17.15	14	3.39	87
Mo	<7.08		<7.08		<7.08		<7.08		<7.08	
Cd	<0.280		<0.280		<0.280		<0.280		<0.280	
Sn	<0.107		1.95	4	2.50	31	3.40	16	<0.107	
Sb	<0.252		1.19	11	0.41	29	0.544	16	<0.252	
Cs	1.92	11	1.91	16	2.51	29	0.579	48	1.26	26
Ba	82.7	3	178	15	159	24	45	59	116	11
La	17	8	19.9	18	26.5	24	11.4	20	14.4	3
Ce	32.2	10	43.7	16	56.7	23	26.5	20	28.6	3
Pr	3.93	8	5.19	15	6.69	23	3.14	19	3.31	2
Nd	14.2	8	19.34	13	24.97	22	11.7	18	11.9	4
Sm	2.65	11	3.46	11	4.38	21	2.3	21	1.99	3
Eu	0.352	14	0.508	17	0.626	17	0.233	25	0.129	25
Gd	1.82	8	2.43	12	2.9	20	1.47	19	1.27	11
Tb	0.31	8	0.425	10	0.456	21	0.261	29	0.173	17
Dy	1.67	9	2.43	11	2.54	22	1.58	35	0.901	17
Ho	0.324	10	0.465	8	0.492	18	0.306	36	0.155	16
Er	0.91	15	1.39	3	1.44	19	0.962	34	0.447	25
Tm	0.141	16	0.196	9	0.21	18	0.137	29	<0.0747	
Yb	1.03	13	1.52	8	1.62	23	1.17	24	0.413	19
Lu	0.155	15	0.208	8	0.248	23	0.167	38	5.70E-02	18
Hf	4.96	10	6.27	1	8.76	1	7.83	1	5.03	11
Tl	<0.149		0.258	41	0.298	45	0.215	84	0.167	43
Pb	5.23	18	10.6	2	30.5	8	11.5	25	9.61	4
Bi	<0.657		<0.657		<0.657		<0.657		<0.657	
Th	6.58	14	10.3	10	10.9	20	12.0	5	8.08	4
U	2.03	5	3.37	2	4.58	2	3.68	2	2.22	2

[a]Represents n=6; Batch 2 (triplicate), Batch 4 (triplicate)
[b]Represents n=4; Batch 2 (1), Batch 4 (triplicate)
[c]Represents n=4; Batch 2 (1), Batch 4 (triplicate)
[d]Represents n=3; Batch 4 (triplicate) [e]Represents n=3; Batch 4 (triplicate)

Table 5.5d: Sample *3.12 top* replicates measured elemental concentrations and precision (%RSD). Values shown as "<…" indicate the measurements were <LOQ, not detected (ND).

Batch	Batch 2 (n=3)		Batch 4 (n=3)		Combined batches (N=6)	
	mg/kg	RSD (%)	mg/kg	RSD (%)	mg/kg	RSD (%)
Al	6000	10	4850	17	5430	17
Sc	2.12	11	2.01	6	2.06	9
Ti	2690	4	2710	3	2700	3
V	13.0	5	12.4	5	12.7	6
Cr	9.33	8	10.5	13	9.94	12
Mn	49.9	4	50.6	3	50.3	3
Fe	1520	3	1590	2	1560	3
Co	<1.47		<1.47		<1.47	
Cu	<8.83		<8.83		<8.83	
Zn	<8.04		<8.04		<8.04	
Rb	15.2	3	15.5	4	15.3	3
Sr	21.6	11	21.9	14	21.8	11
Y	8.19	6	9.01	12	8.60	10
Zr	157	8	174	5	165	8
Nb	4.64	2	6.06	7	5.35	15
Mo	<7.08		<7.08		<7.08	
Cd	<0.280		<0.280		<0.280	
Sn	<0.107		<0.107		<0.107	
Sb	<0.252		<0.252		<0.252	
Cs	2.02	4	1.81	14	1.92	11
Ba	83.6	4	81.8	3	82.7	3
La	16.4	3	17.5	10	17.0	8
Ce	30.7	4	33.7	12	32.2	10
Pr	3.81	2	4.06	11	3.93	8
Nd	13.7	2	14.7	11	14.2	8
Sm	2.49	3	2.80	13	2.65	11
Eu	0.348	4	0.356	22	0.352	14
Gd	1.73	5	1.91	8	1.82	8
Tb	0.298	5	0.322	10	0.310	8
Dy	1.58	6	1.77	8	1.67	9
Ho	0.308	1	0.341	13	0.324	10
Er	0.846	8	0.974	17	0.910	15
Tm	0.130	9	0.151	19	0.141	16
Yb	0.969	8	1.10	14	1.03	13
Lu	0.144	16	0.165	13	0.155	15
Hf	4.54	6	5.38	4	4.96	10
Tl	<0.149		<0.149		<0.149	
Pb	4.93	5	5.52	24	5.23	18
Bi	<0.657		<0.657		<0.657	
Th	5.92	2	7.23	13	6.58	14
U	1.98	3	2.08	5	2.03	5

Table 5.5e: Soil type 4 replicates measured elemental concentrations and precision (%RSD). Values shown as "<…" indicate the measurements were <LOQ, not detected (ND).

Sample	4.4 sub (Qa/Qha)[a]		4.8 sub (Qa/Qha)[b]		4.9 top (Qa/Qha)[c]		4.13 top (Qa/Qpao)[d]	
	mg/kg	RSD (%)	mg/kg	RSD (%)	mg/kg	RSD (%)	mg/kg	RSD (%)
Al	28200	28	7120	8	6120	27	27500	17
Sc	4.76	21	2.88	9	1.94	15	2.72	7
Ti	3840	2	878	29	4050	33	3740	2
V	56.1	3	10.4	15	22.5	14	51.8	2
Cr	48.8	3	16.9	2	17.4	4	30.4	6
Mn	637	11	47.1	5	148	4	404	3
Fe	25300	3	3040	2	4150	3	25600	3
Co	10.9	4	0.638		1.34		4.29	28
Cu	13.7	10	4.31		8.1		10.4	14
Zn	58.2	11	5.30		11.1	17	35.2	5
Rb	67.9	20	22.7	22	20.3	6	92.7	26
Sr	27.2	26	14.9	21	16.1	15	30.9	22
Y	9.63	35	13.4	19	5.80	8	3.54	35
Zr	369	6	256	2	148	5	367	3
Nb	18.8	2	0.667	58	5.24	45	23.0	3
Mo	<7.08		<7.08		<7.08		<7.08	
Cd	<0.280		<0.280		<0.280		<0.280	
Sn	6.82	4	<0.107		<0.107		7.22	2
Sb	<0.252		<0.252		<0.252		<0.252	
Cs	4.60	63	1.94	6	1.61	18	3.89	50
Ba	281	18	90.8	6	107	4	247	25
La	24.5	17	22.4	12	15.7	11	10.9	25
Ce	48.3	15	43.8	13	32.4	12	27.4	22
Pr	6.33	16	5.19	12	3.63	9	2.73	18
Nd	23.2	18	18.9	10	13.3	10	9.65	18
Sm	4.29	18	3.41	12	2.30	14	1.72	12
Eu	0.342	35	0.385	15	0.216	15	8.00E-02	37
Gd	2.84	22	2.35	12	1.51	11	1.04	26
Tb	0.453	25	0.404	13	0.221	6	0.159	23
Dy	2.46	32	2.37	15	1.23	12	0.943	32
Ho	0.464	35	0.479	15	0.225	13	0.174	32
Er	1.34	39	1.42	15	0.622	14	0.535	32
Tm	0.194	42	0.232	19	9.32E-02	19	7.72E-02	43
Yb	1.56	35	1.62	18	0.730	11	0.806	29
Lu	0.240	33	0.271	17	0.105	7	0.115	50
Hf	11.2	3	7.93	5	4.10	2	11.5	6
Tl	0.771	29	<0.149		<0.149		0.617	41
Pb	27.7	3	4.78	4	6.87	3	29.8	5
Bi	0.709	14	<0.657		<0.657		0.718	3
Th	22.5	8	10.4	15	6.61	11	21.3	11
U	15.0	1	3.22	7	2.02	5	10.8	5

[a]Represents n=4; Batch 3 (1), Batch 4 (triplicate)
[b]Represents n=3; Batch 3 (triplicate)
[c]Represents n=4; Batch 3 (1), Batch 4 (triplicate)
[d]Represents n=4; Batch 3 (1), Batch 4 (triplicate)

Consistent with expected natural variability of environmental samples, soils results were less precise for some elements within and between batches than the SRM BHVO2 and NIST2711a replicates. Excluding ND (<LOQ) elements, precision was generally optimal throughout the sample replicates for higher concentration measurements (RSD≤10%), excepting for Al (RSD<50%). While Al measurements of soil type 2 (granite derived soils) replicates were the least precise, higher concentration elements were generally of greater precision than in the granite SRM AC-E. Precision for lower concentration elements including REE across most soil replicates was generally RSD<50%, commonly RSD=20-40%. For the soil analysed twice in triplicate (*3.12 top*, Table 5.5d), the greatest variations in reproducibility were for Al and REE, consistent with the trend found in SRMs. Within-batch Al precision ranged from RSD=0-25%, while overall Al precision ranged from 10-48%. Once more consistent with the trend in SRM results, and with few exceptions, Fe and the HFSE Ti, Zr, Nb, Hf and U had relatively high precision (RSD<12%). There was little systematic effect found on precision due to organic matter content (range 1.43 to 44.0% dry soil weight; Appendix 9). Reproducibility was generally more precise for sedimentary geology origin soils (soil types 3 & 4) than for igneous geology origin soils (soil types 1 & 2).

While variability of element concentration measurements was more evident in the replicate soil (environmental) samples than in the SRMs BHVO2 and NIST2711a, the results were considered sufficiently systematic and reproducible to be fit for the purpose of soil type “fingerprinting” (after Marx & Kamber, 2010). The poor experimental recovery and reproducibility in the granite SRM AC-E were atypical of the experimental methods. These results were to be further considered following statistical work with the data should statistical discrimination prove difficult.

5.2.4 Development of the working datasets

The full soil sample elemental datasets (Appendix 8) and SRMs results were considered for elements not detected (ND) based on LOQ (Table 3.6). Other ND results in SRMs that were coincidental with ND in soils are explainable by low published values rather than poor detection for the digestion method used.

Elemental concentrations data considered in selecting the working elemental dataset are shown in Table 5.6 below. SRM data was included to identify elements that were ubiquitously ND, poorly detected generally or only ND in SRMs or soils.

From these results, Mo, Cd, Sb, Tm, Lu and Bi were considered ND throughout according to LOQ and removed from the working datasets, retaining 35 elements, whereas the trace elements Cu and Zn (ND in many samples) had relatively high LOQ. Other elements for which ND results were less consistent between sources and which were considered distinctive between sources were also retained. Six of these (Co, Nb, Sn, Nd, Tb and Ho) became" properties" included in the 13-element "fingerprint" that distinguished the soils. Mean concentrations (RSD) of elements by soil type comprising the working dataset is shown in Table 5.7. Complete elemental concentration data are shown in Appendix 8.

Table 5.6: Elements not detected (<LOQ) by number of samples per soil type and SRM. Elements removed from the working dataset are highlighted.

Soil /SRM (total samples)	S type 1 (N=18)	S type 2 (N=20)	S type 3 (N=40)	S type 4 (N=30)	BHVO2 (N=9)	AC-E (N=9)	NIST2711a (N=11)
Al							
Sc							
Ti							
V						9	
Cr						8	
Mn							
Fe							
Co		1	22	5		9	
Cu		4	29	8		9	
Zn			9	3			
Rb							
Sr		3				9	
Y							
Zr							
Nb			5	2			
Mo	18	20	39	30	9	9	11
Cd	18	16	39	22	9		
Sn	2		10	14			
Sb	13	18	20	20	9	1	
Cs					9		
Ba							
La							
Ce							
Pr	3	10	4				
Nd		2					
Sm		1					
Eu	1	9	4	1			
Gd		1					
Tb	3	8	3	2			
Dy							
Ho	1	4	2				
Er							
Tm	6	8	5	6			
Yb							
Lu	5	6	2	4			
Hf							
Tl	1		5	3	9		
Pb							
Bi	16	11	39	23	9	9	
Th							
U							

Table 5.7: Element mean concentration values (mg/kg, RSD) of working datasets. Elements identified in the fingerprint (5.3.2 below) are highlighted.

Soil type	Soil type 1		Soil type 2		Soil type 3		Soil type 4	
Element	Mean	RSD (%)	Mean	RSD (%)	Mean	RSD (%)	Mean	RSD (%)
Al	40314	47	41075	56	19185	56	23356	59
Sc	13.3	57	4.60	56	3.50	38	4.44	74
Ti	5561	41	5267	31	3526	38	3108	34
V	183	32	70.6	42	53.7	59	56.6	71
Cr	112	74	29.1	49	46.9	55	42.3	57
Mn	2107	81	1040	117	190	143	490	83
Fe	53397	35	33541	48	13426	88	18607	68
Co	39.8	38	6.14	74	1.99	88	9.67	91
Cu	47.4	35	16.0	48	9.03	67	18.2	82
Zn	81.0	34	51.7	54	16.0	69	50.3	96
Rb	13.9	93	51.9	57	24.6	54	47.1	59
Sr	35.3	60	38.1	96	23.9	114	26.7	32
Y	4.24	55	2.92	76	6.78	46	7.48	54
Zr	136	40	370	23	201	31	196	43
Nb	8.83	38	26.5	35	8.73	53	9.32	80
Sn	1.62	41	8.96	61	2.58	60	2.65	100
Cs	1.40	99	5.29	60	2.28	59	3.12	70
Ba	191	42	252	81	124	63	258	39
La	4.99	61	5.12	100	12.3	56	15.8	52
Ce	11.4	52	11.9	86	25.7	54	31.9	49
Pr	1.36	67	1.28	102	3.09	53	4.01	50
Nd	5.25	54	4.59	95	11.6	53	15.0	50
Sm	1.29	64	1.13	85	2.15	51	2.77	51
Eu	0.40	123	0.28	170	0.30	60	0.35	66
Gd	1.05	64	0.81	83	1.48	47	1.89	54
Tb	0.32	135	0.27	146	0.26	46	0.30	55
Dy	1.27	57	0.95	76	1.54	42	1.77	55
Ho	0.36	107	0.32	148	0.32	44	0.34	57
Er	0.82	66	0.67	85	0.93	43	0.99	53
Yb	0.85	65	0.76	62	1.05	42	1.11	52
Hf	3.90	39	11.2	22	6.00	30	5.94	48
Tl	0.32	50	0.86	34	0.38	58	0.54	63
Pb	12.7	26	30.7	28	13.3	59	29.6	201
Th	3.24	46	7.49	94	6.64	44	10.5	76
U	1.49	36	7.65	58	2.88	29	5.42	101

5.3 Statistical results

5.3.1 Preliminary tests

Normality tests were conducted on the 35-element working elemental datasets prior to testing for redundant fingerprint properties using non-parametric statistical methods. Normality tests conducted on soils datasets and the combined working fingerprint dataset confirmed non-normal distributions at *alpha*=0.05 for most element concentrations across the soils datasets, confirming the need for non-parametric statistical procedures.

Each potential fingerprint property was tested for significant differences between soil types to eliminate any redundant tracers. The *Kruskal-Wallis* test (*alpha*=0.05), using *Monte-Carlo* simulations and multiple pairwise comparisons of the *Steel-Dwass-Critchlow-Fligner* procedure (two-tailed test), were conducted on the working dataset of 35 elements. In scrutiny of relative values, special attention was given to discrimination between soil types 3 and 4, seen as the most challenging since probably >50 % of type 4 soils (Quaternary sediments) were derived from soil type 3, according to area of catchment occupied. Probable redundant elements Eu, Tb, Ho and Yb were further tested between soil types. Eu, Ho and Yb were specifically retained in the statistical process because this further testing showed power to distinguish soil types 3 and 4.

5.3.2 Selection of the fingerprint

Models were explored using parameters chosen and stated in Table 3.7 until satisfied the optimal model and fingerprint had been identified. The objective was to optimise the probability distribution (minimise Wilk's lambda), minimise the number of properties comprising the fingerprint and minimise the numbers of reclassified samples while discriminating the soil types with 95% confidence.

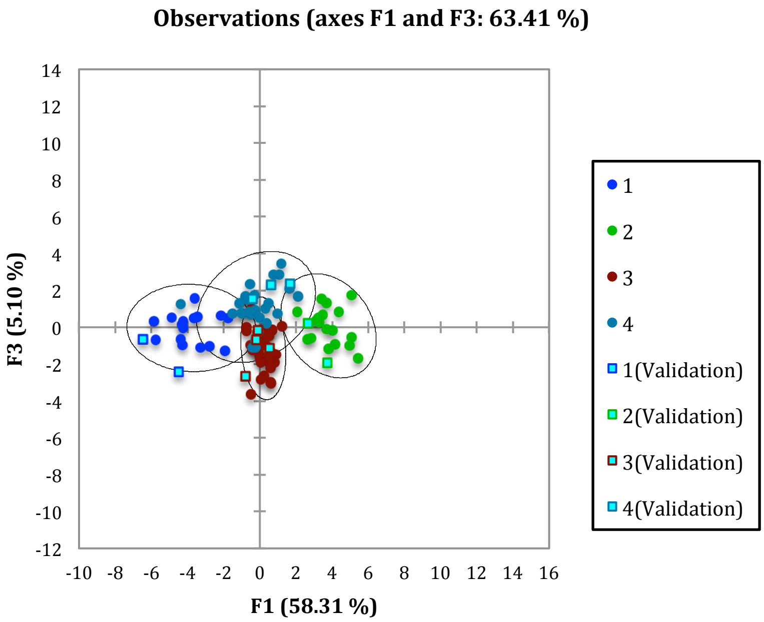
The fingerprint according to the final model was comprised of major elements Al, Ti, Mn and Fe, trace elements V, Co, Rb, Zr, Sn and Ba, and rare earth elements Nd, Tb and Ho (13 properties). Of these, Ti and Zr are high field strength elements (HFSEs). These fingerprint properties were highlighted in Table 5.7 (above). Including the 11 validation samples, the optimal *Discriminant Analysis* model (Table 5.8) correctly classified 87% (94) of the total 108 samples with 95% confidence using a 13 property fingerprint.

Table 5.8: Specifications and results of the final fingerprint model.

Computation ID (file)	Fingerprint properties (n=13)	Wilk's lambda	Validation set (*Group*) (n=11)	Samples correctly classified[a] (n=94)	Samples reclassified post validation (n=14)
DA2 (DFArawdataThesis.xlsx)	Al, Ti, V, Mn, Fe, Co, Rb, Zr, Sn, Ba, Nd, Tb and Ho ⁻	0.012	Subsoils: 1.9, 2.1, 3.10, 3.12, 4.4 Topsoils: 1.14, 2.3, 3.9, 3.26, 4.4, 4.5	87%	Subsoils: 3.8, 3.15, 4.9, 4.12, 4.13 Topsoils: 1.13, 2.10, 3.10, 3.21, 3.23, 4.8, 4.9, 4.13, 4.16

[a]Samples comprising the validation sample set (n=11; Table 5.9) are included as "correctly classified."

The optimal model according to the specifications in Table 5.8 was visualised in the *Observations* and *Centroids* plots (Figure 5.6). Note that these diagrams are two-dimensional (2 axes) representations of a multi-dimensional field (3 axes). Outliers have been reduced by the model and separation of soil types can be seen.



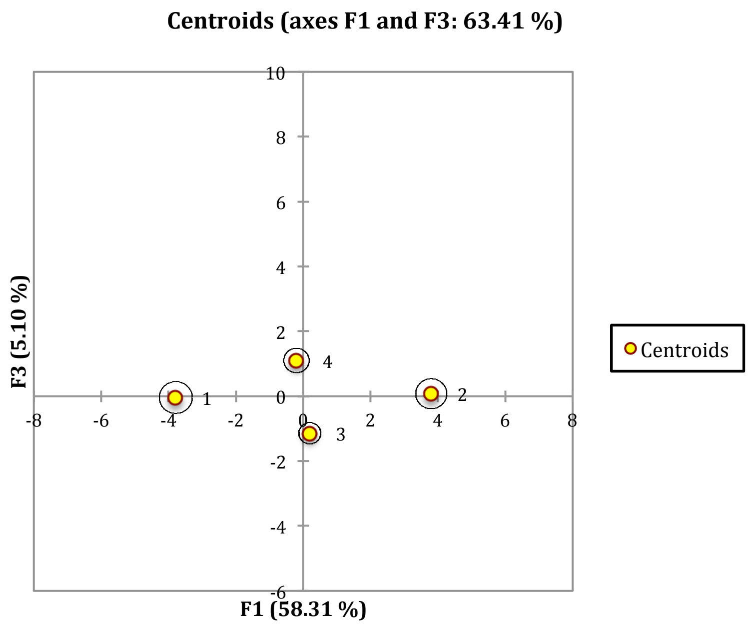


Figure 5.6: Observations and centroids plots visualising the final fingerprinting model (Addinsoft™ XLSTAT). The validation set is highlighted in the Observations plot.

In the observation plot of the model, the set of validation samples (highlighted) are shown as well as the 95% confidence elipses for the distributions in each soil category/type. The second plot shows two different measures of central tendency in the model: the centroid (vector of means of the variables used in the fingerprints) corresponding to each category (soil type) and the confidence circles for the means of the samples. A centroid is analogous to a centre of gravity for each category in the multi-dimensional space, while the circles indicate the location of the means of the variables in the space.

The statistics show 95% confidence in the *a priori* classification using this fingerprint. It was found the critical operational parameter was the composition of the validation set. The final model was selected for closely corresponding centroids and optimisation of confidence elipses in the *Observations* plots for minimum reclassified samples and maximum statistical certainty. Particular attention was paid in developing a model to best distinguish soil type 4 samples from those of the parent materials (the other 3 types), particularly soil type 3 that occupies >50% of the physiographical study catchment.

The precise fit of the samples (*n* per soil type) to the *a priori* classifications comprising the validation set and the aggregated probabilities of fit for the sample set on the premise of an unbiased weighting of classifications are shown in Tables 5.9 and 5.10 respectively. Classification membership probabilities for samples of the working dataset, including those reclassified, are shown in the crossvalidation table (Appendix 10).

Table 5.9: Confusion matrix for the validation sample (Addinsoft^{TM} *XLSTAT*).

from \ to	S1	S2	S3	S4	Total	% correct
S1	2	0	0	0	2	100.00%
S2	0	2	0	0	2	100.00%
S3	0	0	4	0	4	100.00%
S4	0	0	0	3	3	100.00%
Total	2	2	4	3	11	100.00%

Table 5.10: Confusion matrix for the cross-validation results (Addinsoft™ *XLSTAT*).

from \ to	S1	S2	S3	S4	Total	% correct
S1	22.73	0	0	1.516	24.25	93.75%
S2	0	22.90	0	1.347	24.25	94.44%
S3	0	0	20.88	3.368	24.25	86.11%
S4	0.8981	1.796	3.593	17.96	24.25	74.07%
Total	23.63	24.70	24.47	24.19	97.00	87.09%

The respective percent of correct classification of soil types 3 (86%) and 4 (74%) was the best outcome found by varying the validation set in *Discriminant Analysis* runs. Considering the absence of tracer weightings, the small number of samples, the inclusion of a fourth geological classification derived from the remaining three and use of *Monte Carlo* (non-correlated probability) techniques, the overall 87% soil sample classification certainty of the final result is reasonable in comparison to many other studies based on elemental properties. For example the range of percentage correct soil sample classifications in other similar studies included 93% of samples (Collins *et al.*, 2001), 96% (Carter *et al.*, 2003) and 100% (Collins *et al.*, 2012). Improved digestion techniques and element recovery could improve the chemical signature and discriminatory power. While incomplete dissolution is a known problem in the field (e.g. Takei *et al.*, 2001; Nath *et al.*, 2009) and post-digestion centrifugation is mentioned in studies, few such papers discuss the issue.

5.3.3 Analysis of soil reclassification

Soil types 3 and 4 were the least well discriminated. Of the 14 samples reclassified by the model (Table 5.8) seven were reclassified as soil type 4, four were reclassified as soil type 3, one was reclassified as soil type 1 and two as soil type 2. Topsoils (9) were more likely to be reclassified than subsoils (5). Site factors apparently systematic in sample reclassification are shown in Table 5.11. Complete sample site details are found in Appendix 3.

Table 5.11: Analysis of site factors in reclassification.

Sample	R[a]	1	2	3	4	Catch-ment[b]	Mapped surface geology	Situation
3.8 sub	4	0.000	0.000	0.414	0.586	BoD	Psp	Open pasture, low hill
3.15 sub	4	0.000	0.000	0.278	0.722	SEsk	ODsm	Mid altitude burnt out pine plantation
4.9 sub	3	0.000	0.000	0.661	0.339	BoD	Qrc/Qha	Close to river, imp. pasture
4.12 sub	1	1.000	0.000	0.000	0.000	BoD	Qrc/Qha	Close to river, imp. pasture
4.13 sub	2	0.000	0.862	0.008	0.130	SEsk	Qa	River terrace high in granite country
1.13 top	4	0.002	0.000	0.179	0.819	SEsk	Jdtm	Exposed dolerite crag
2.1 top (mean)	4	0.000	0.043	0.166	0.791	SEsk	Dgrt	Tributary S. Esk headwaters
3.10 top	4	0.000	0.000	0.384	0.616	BoD	ODsm	Hills near St Marys
3.21 top	4	0.000	0.000	0.345	0.655	BoD	ODsm	Hills near St Marys
3.23 top	4	0.000	0.000	0.020	0.980	SEsk	ODsm	High altitude S. Esk
4.8 top	3	0.000	0.000	0.872	0.128	SEsk	Qa	S. Esk flats near ODsm
4.9 top (mean)	3	0.000	0.000	0.953	0.047	BoD	Qrc/Qha	Close to river, imp. pasture
4.13 top (mean)	2	0.000	0.834	0.022	0.144	SEsk	Qa	River terrace high in granite country
4.16 top	3	0.000	0.000	0.950	0.050	SEsk	Qa	Forested river terrace near ODsm

[a]Reclassification [b]SEsk: South Esk; BoD: Break O'Day

Several reclassifications occurred where sample sites were proximal to the river (5) or to adjoining non-target surface geology (3). The only reclassified type 1 soil sample (topsoil) was near the summit of an exposed crag (dry sclerophyl forest). The only reclassified soil type 2 (topsoil) was centrally located within the target surface geology (sparse regrowth forest) and the sample was processed in replicate, therefore the reclassification has no ready explanation. The two soil type 3 samples in the South Esk catchment reclassified as soil type 4 probably indicate inaccurate boundary locations between the target surface geology and soil type 4. Whereas the reclassification of a target type 4 sample as type 2 was consistent with the mapped Land systems code third digit, although its physiography was that of a Quaternary river terrace (see 5.1.3). Two of the topsoils of the six soil type 3 sample sites located in the St Marys hills were reclassified as soil type 4, as was one subsoil lower in the Break O'Day catchment. No systematic reason was apparent for these three samples; two sites were improved pasture and one was eucalypt forest regrowth. Further density of samples is recommended on smaller, less typical, outcrops of soil type 3.

Eight of the 14 reclassified soils had notable LOI value anomalies (Table 5.12; Appendix 9). Compared with means for soil types by sub- and topsoils, organic matter and carbonates (LOI) anomalies included three subsoils low in organic matter, two subsoils high in organic matter, one topsoil high in organic matter and two topsoils low in carbonates. High organic content did not systematically correspond with low carbonates content. Five soils were close to mean for both values.

Table 5.12: Analysis of LOI factors in reclassification. Means shown are per soil depth for each soil classification.

LOI (% wt.)	Organic matter		Est. carbonates	
	Sample	Mean (RSD %)	Sample	Mean (RSD %)
3.8 sub	1.94	5.7 (58)	0.321	0.839 (49)
3.15 sub	2.27		0.461	
4.9 sub	3.56		0.577	
4.12 sub	15.3	8.09 (85)	1.70	0.837 (62)
4.13 sub	15.6		1.04	
1.13 top	36.8	30.3 (53)	1.05	1.51 (46)
2.1 top	24.9	29.7 (37)	1.51	1.61 (50)
3.10 top	11.5		0.846	
3.21 top	7.7	11.8 (64)	0.609	0.663 (51)
3.23 top	14.6		0.965	
4.8 top	8.42		0.142	
4.13 top	44.0	14.9 (67)	1.07	0.864 (61)
4.16 top	9.63		0.163	

From these analyses, the full extent of the margins of soil type 4 cannot be determined using elemental fingerprinting. A second observation concerning soil type 4 is the reclassification of three of the six samples of Qrc/Qha, a subset of surface geology found only in Break O'Day catchment (Figure 3.9). If required, increased sampling density of the colluvium (Qrc) of Qha should better distinguish the sub-type and show if a fifth soil classification may be required.

While the model has generally validated the digital soil mapping, it is suggested that a greater number of soil type 4 samples may have improved the four soil type fingerprint model, given the discrimination considerations of Quaternary sediments. Alternatively, probability (stratified random) sampling across soil type 4 may ensure representative sampling of the two *subsets* of alluvial sediments (Jackson, 2006). However, it would require a wide selection of accessible potential sample sites from which to sample randomly. The analysis could also be run with two alluvium *types*, totalling five soil types, to compare the discriminatory power.

5.4 Erosion hazard analysis in context

5.4.1 Erosion hazard mapping of the Tamar basin

While it was not possible as part of the present study to re-run the actual *WaterCAST* computer modelling of sediment flux to the Tamar estuary using geological (soil type) classifications, the erosion hazard layer used in the modelling was examined using the project GIS for the Tamar basin (Figure 5.7) and in detail for the Upper South Esk study area (Figures 5.8 & 5.9). Data were supplied by DPIPWE (Department of Primary Industries, 2016).

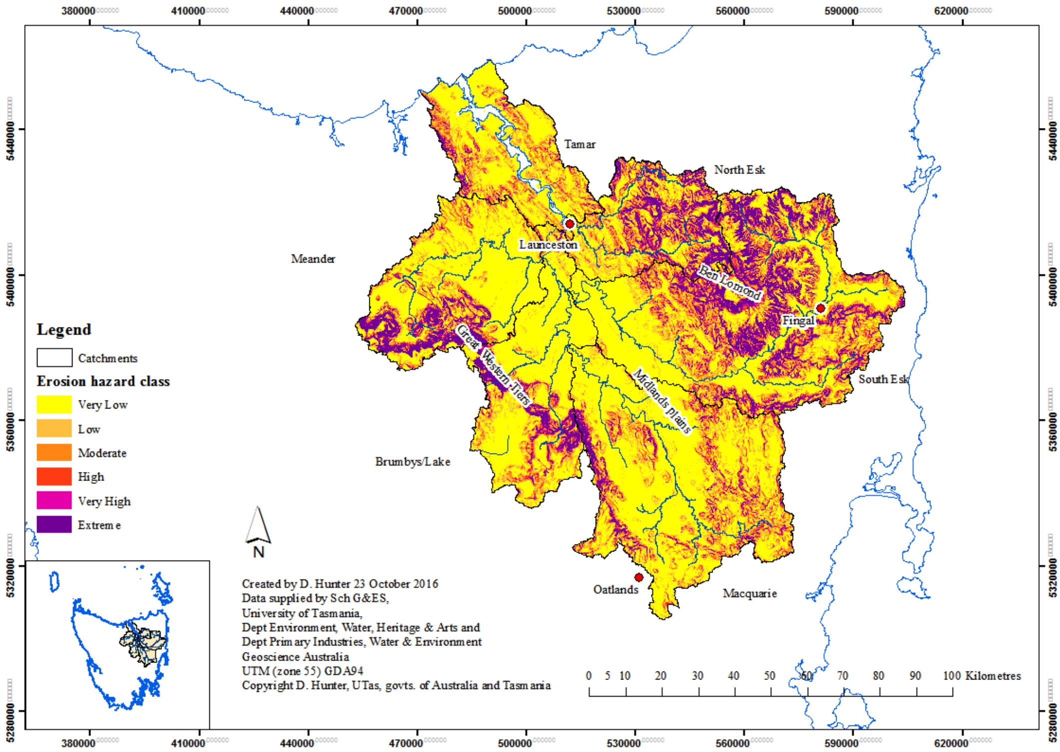


Figure 5.7: Erosion hazard mapped in six classes, as used in *WaterCAST* modelling, Tamar basin.

Erosion hazard is considered very low over much of the Midlands plains, however, as indicated in *WaterCAST* sediment flux modelling (Figure 4.14), highlands of the Meander, North Esk and South Esk catchments rate highest in erosion hazard. Much of the highest hazard rating is found in the upper South Esk pilot study area (Figures 5.8 & 5.9 below). Erosion hazard data were overlaid on both 1:500,000 scale geological mapping and land use. Geological mapping (soil types) is considered first.

5.4.2 Geological and erosion hazard mapping, upper South Esk catchment

The results from geological mapping overlaid on erosion hazard data are shown in Figures 5.8, 5.9 and 5.10.

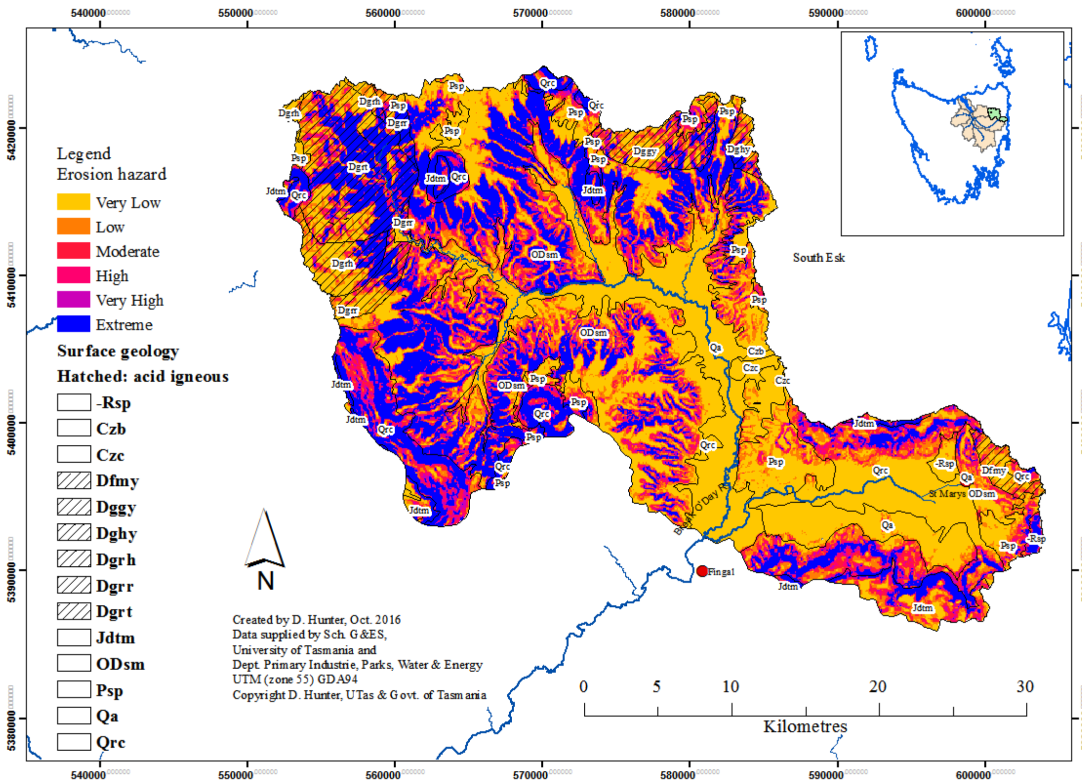


Figure 5.8: Erosion hazard mapped in six classes, upper South Esk catchment. The labelled geological units are outlined, with acid igneous units hatched.

Erosion hazard is considered severe (indigo blue) across the steep mountain flanks, especially soil type 1 colluvium derived of dolerite and the sides of the deeply incised gullies of soil types 2 and 3 at the mid-altitudes. While 37% of the catchment is very low erosion hazard, over 24% is classed extreme (Figure 5.9).

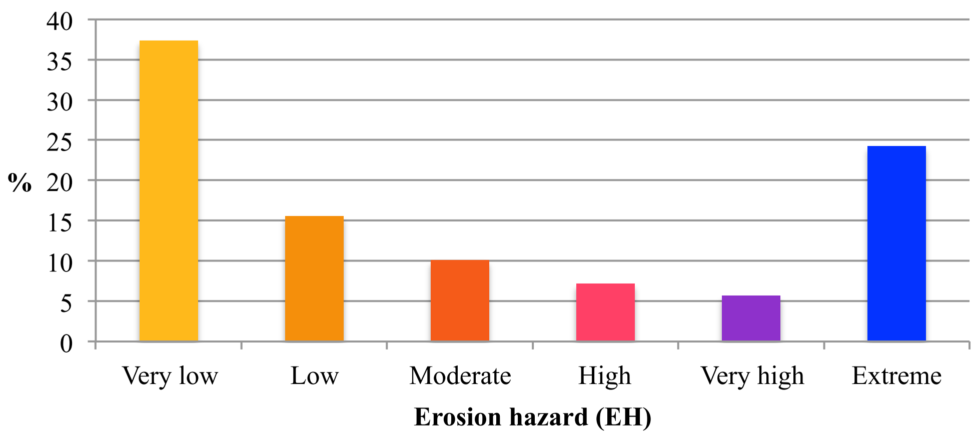


Figure 5.9: Erosion hazard by percentage cover, upper South Esk catchment.

Examination of the surface geology data of the catchment (1:500,000) shows that ODsm sediments (soil type 3) host 128 km^2 of the 246 km^2 severe erosion class, Quaternary colluvium (Qrc) (distributed between soil types 1 and 4) hosts 55 km^2 and granites (soil type 2) host 42 km^2 (Figure 5.10).

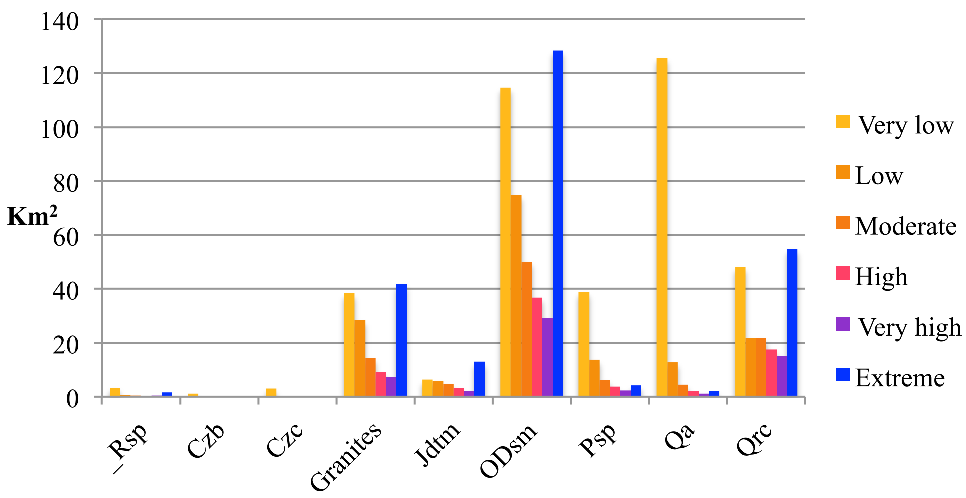


Figure 5.10: Erosion hazard (km^2) by 1:500,000 scale geological units, upper South Esk catchment.

Therefore, it is suggested that while acid igneous (granite-derived) soils have received attention in the literature as highly erodible soils (Laffan & Neilsen, 1997; Laffan *et al.*, 1998; Laffan *et al.*, 2003), the digital data and overlay of the erosion hazard layer suggest that type 3 soils and Quaternary dolerite-derived colluvium (Qrc/Jdtm) soils also warrant close attention in erosion risk mitigation.

The data were then considered as erosion hazard classes by soil type and percentage of the catchment (Figure 5.11).

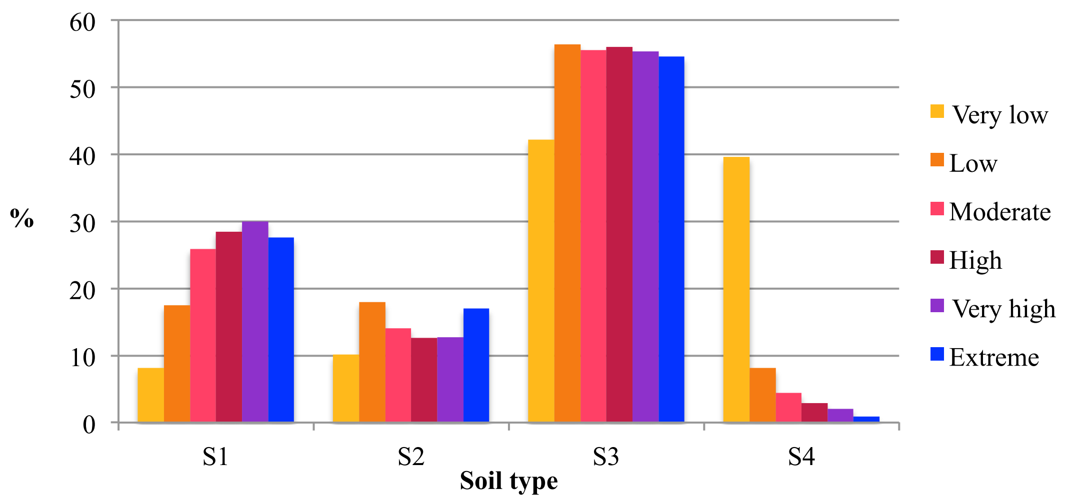


Figure 5.11: Erosion hazard by soil type: percentage cover of the upper South Esk catchment.

Soil type 1 (19% of the catchment) has the greatest disproportion in higher erosion hazard although soil type 3 (50% of the catchment) has greatest coverage of higher erosion hazard. Soil type 2 covers 14% and soil type 4 covers 17% of the catchment respectively. It is apparent that classification by soil type facilitates scrutiny of erosion hazards and could be used in erosion modelling. Such classification simplifies geological units and soil mapping, while allocating units such as colluvium (Qrc) to the correct soil type (i.e. S1 or S4) according to the parent materials.

5.4.3 Land use mapping and erosion hazard, upper South Esk catchment

Recent and current land use cartography was shown in Chapter 4 (Figures 4.16 & 4.17). Here, land use data is related to erosion hazard (Figure 5.12 & Table 5.13) and (finally) soil type is overlain on land use (Figure 5.13).

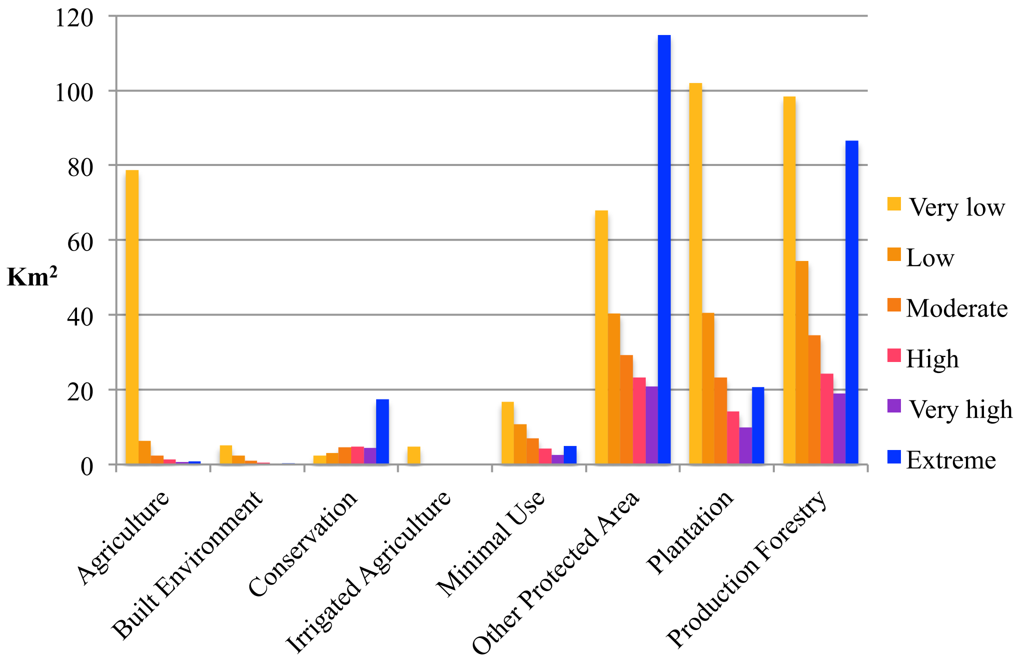


Figure 5.12: Erosion hazard by land use (km^2), upper South Esk catchment.

Table 5.13: Land use and erosion hazard (km^2), upper South Esk catchment.

Land use / EH class	Agric	Built Env.	Conserv-ation.	Irrig. Agri.	Min. Use	Other Prot. Area	Plant-ation	Prod. Forestry
Very low	78.7	5.09	2.38	4.78	16.8	67.9	102	98.3
Low	6.26	2.4	3.09	0.01	10.8	40.3	40.5	54.4
Moderate	2.43	1.01	4.62		7.02	29.3	23.2	34.5
High	1.37	0.47	4.85		4.21	23.3	14.1	24.2
Very high	0.62	0.22	4.38		2.50	20.9	9.83	19.0
Extreme	0.85	0.39	17.4		5.01	114	20.6	86.6
Total	90.2	9.58	36.7	4.78	46.3	297	210	317

From the above figure and table, it can be seen that land use management proscription, *vis-a-vis* the *Forest Practices Code* (2005), has seen a considerable area of land lately identified as extreme erosion hazard designated as informal reserves (*Other Protected area*) since 2002 (Figures 4.18 & 4.19). However, much of this land had been previously subjected to intensive forestry uses and much remains in

Production forestry or *Plantation* under older management regimes (1.1, Figures 1.7 & 1.8). The area of extreme erosion hazard classification land in (formal) *Conservation* tenure is exceeded by that under *Plantation*.

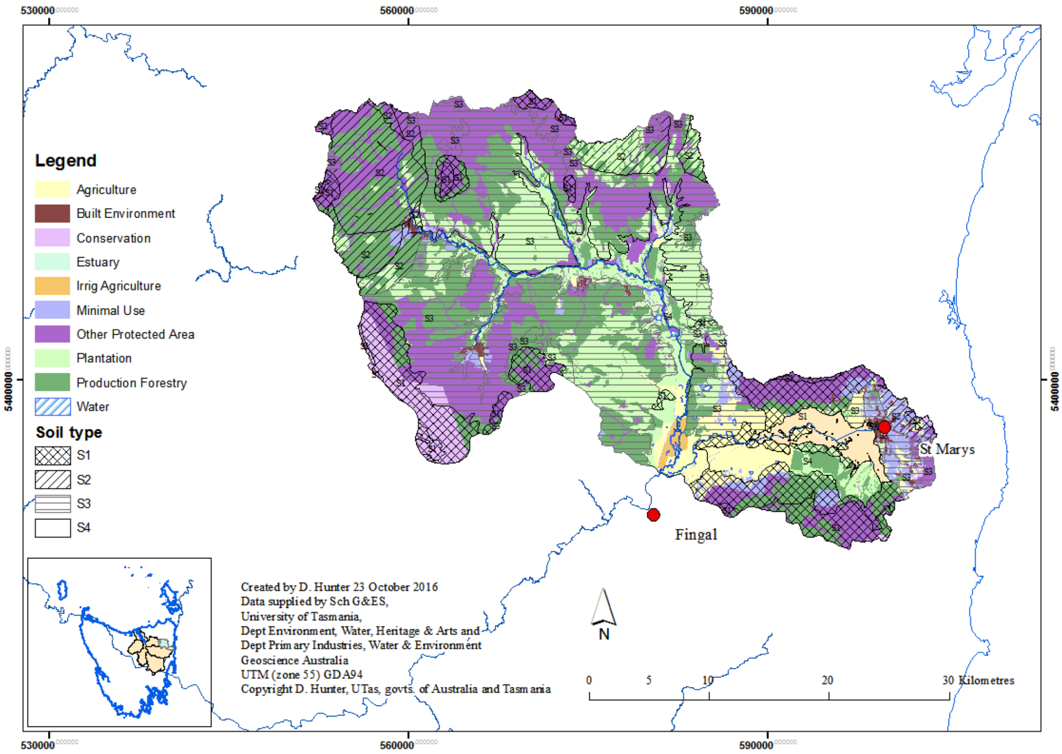


Figure 5.13: Soil type over land use, upper South Esk catchment.

From Figures 5.8 and 5.13, little of the extreme erosion class land on granite-derived soils (S2) has been placed into the recently dedicated informal reserves. On soil type 3, much of the erosion-vulnerable southwestern topography from the flanks of Ben Lomond (Figure 4.1) east to Tower Hill is now under informal reserves (Figure 5.13). Informal reserves also occur as roadsides strips and large areas of low erosion hazard sub-alpine moorland and scrub in the north (Figure 5.13). However, while the scale of the 2013 land use spatial data is stated to vary with the intensity of land use (Appendix 1), little systematic location of informal reserves i.e. on steep sided gullies (or areas dense with steep sided gullies) can be attributed outside the Break

O'Day catchment. Informal reserves in the Break O'Day catchment apparently correspond with scenery values more than erosion hazard (Figure 5.13). Further, during this study, across the headwaters of the South Esk in the west of the catchment where soil type 3 is dominated by production forestry land use with a minor component of plantation, forestry was frequently observed proceding without establishment of streamside reserves (Figures 1.7 & Figure 5.14).

Figure 5.14: Plantation land use on extreme erosion hazard class, soil type 3 (ODsm) (2011). Tier Creek near Joy Road sample site 3.14 (altitude approximately 800 m).

Investigation to resolve land management implications is warranted by modelling land use and soil type at increased resolution.

5.5 Conclusions

In summary, the experimental work covered by Chapter 5 has fulfilled the second, third and fourth objectives of the study. Following multi-component strategic sampling, four distinct soil types based upon current Tasmanian soil mapping in a large (>1,000 km^2) sub-catchment have been confirmed using elemental (geochemical) characterisation techniques (second and third objectives). A GIS query of erosion hazard classes, soil types and land use data provided qualified affirmation that the results of *WaterCAST* modeling of total suspended sediment (TSS) yield based upon land use are reasonable (fourth objective).

Soil sampling in this rugged, remote catchment was opportunistic according to proximity of sites to road access, requiring a rigorous approach in sampling stratification. Post-hoc verification established and confirmed a feasible method for soil sampling fieldwork aimed at chemical soil characterisation. Laboratory results confirmed reproducibility of experimental soils data using practical methods developed to take advantage of the available laboratory resources. The generation of hard (geochemical) data confirming geological mapping provided additional scope for future integrated sediment modeling.

A variety of sample site and soil property measurements enabled close scrutiny and analysis of samples, particularly in the case of atypical probabilistic statistical classification and existing erosion hazard modeling. They included vegetation communities, site physiography, soil physical characteristics, LOI (organic C and carbonate fractionation), sample particle fractionation, and geochemistry “signatures.” Rigour was applied in assessing the reproducibility of laboratory analyses and in statistical distinction of four soil types by their elemental geochemistry.

The above approaches enabled an informed critique of the results of the *WaterCAST* model related to erosion hazard mapping, its attribution of sediment by land use and the assumptions the model was built upon. While Chapter 2 addressed the research questions concerning review of the literature, the experimental components of the project presented in Chapter 5 addressed the remaining questions, encapsulated in the central aim of the project: to facilitate improvement in erosion control in the catchments and siltation in the estuary, including asking whether the *WaterCAST* land use findings were reasonable.

While TEER (Tamar Estuary and Esk Rivers Program, 2015) is primarily concerned with improving erosion control on lowland agricultural land, it has been found that much of the land classed as of extreme erosion hazard consists of 1. high altitude conservation lands not subject to threatening land uses and 2. land that remains in forestry/plantation land use. It has been found that pre-Forest Practices Code (FPC) forestry techniques continue across the catchment, much of it on highly erodible grantire derived soils. There is little evidence of a systematic relationship between environmental factors such as erosion risk and informal reserves under the FPC.

It was found in field and GIS work that mapped classification of land use is substantially uncertain and subject to rapid change. While the literature review suggested the *WaterCAST* land use attribution appeared reasonable, the experimental results suggest that geology would be a more reliable basis for the model and therefore would likely improve its predictions and acceptability in the community.

In critical examination of laboratory and statistical results, it may be seen there is room for improvement in recovery following digestion. Although the robustness and discrimination power of the chemical signatures of the soil types was reasonable (third objective), areas for improvement have been identified in each of the sample procurement, processing and statistical analysis steps. Such improvements could reduce reclassification of samples and improve discrimination.

In context, much of this chapter has focussed on analysis of data generated during this project of potential value with a view to contributing to the government's recent commitment to ongoing improvements in soil information capture (including soil attributes for erosion hazard assessment), targeting Tasmanian regions of high uncertainties and important ecological or agricultural value (Kidd *et al.*, 2015). Further experimental work may resolve uncertainties in the geochemical findings and help improve knowledge regarding soil type 4 geology mapping boundaries. This project's findings suggest sediment inputs to the Tamar estuary would be better understood by updating resolution, precision and accuracy of soils and geological mapping and modeling suspended sediment flux on that basis. Land use mapping should be updated (and henceforth regularly maintained) in areas identified as high sediment yield by *WaterCAST* modeling, and examined for erosion hazard assessment to refine remediation targeting.

Remote sensing (e.g. LIDAR) is part of the new toolkit promising imminent improvements in landscape analysis; improvements that would be impossible by field research alone. However, future higher resolution mapping for land use/erosion management purposes will ideally require ground truthing. The field, desk-top and laboratory research techniques developed and validated during this project are suggested suitable for such use.

5.6 References

Australian Bureau of Rural Sciences (2006). 2001/02 Land Use of Australia, Version 3. Canberra.

Bowie, AR, Townsend, AT, Lannuzel, D, Remenyi, TA and van der Merwe, P (2010). "Modern sampling and analytical methods for the determination of trace elements in marine particulate material using magnetic sector inductively coupled mass-spectrometry." Analytica Chimica Acta **676**: 15-27.

Carter, J, Owens, PN, Walling, DE and Leeks, GJ (2003). "Fingerprinting suspended sediment sources in a large urban river system." The Science of the Total Environment **314-316**: 513-534.

Collins, AL, Walling, DE, Sichingabula, HM and Leeks, GJL (2001). "Suspended sediment source fingerprinting in a small tropical catchment and some management implications." Applied Geography **21**: 387-412.

Collins, AL, Zhang, Y, Walling, DE, Grenfell, SE, Smith, P, Grischeff, J, Locke, A, Sweetapple, A and Brogden, D (2012). "Quantifying fine-grained sediment sources in the River Axe catchment, southwest England: application of a Monte Carlo numerical modelling framework incorporating local and genetic algorithm optimisation." Hydrological Processes **26**: 1962-1983.

Department of Primary Industries, P, Water and Environment (2016). Tasmanian Land Use 2013. P. Department of Primary Industries, Water and Environment. Hobart.

Forest Practices Board (2005). Forest Practices Code. Hobart, Forest Practices Board.

Jackson, S (2006). Research Methods and Statistics: A Critical Thinking Approach. Belmont, USA, Thompson Higher Education.

Kidd, D, Webb, M, Malone, B, Minasny, B and McBratney, A (2015). "**Eighty-metre resolution 3D soil-attribute maps for Tasmania, Australia**." Soil Research **53**: 932-955.

Laffan, MD, Grant, HC and Hill, RB (1998). "Some properties of soils on sandstone, granite and dolerite in relation to dry and wet eucalypt forest types in Northern Tasmania." Tasforests **10**: 49-58.

Laffan, MD, McIntosh, P and Neilson, WA (2003). "Forest soils derived from granite in northern Tasmania: an overview of properties, distribution and management requirements." Tasforests **14**: 1-14.

Laffan, MD and Neilsen, WA (1997). "Soil mapping in Tasmania's State forest." Tasforests **9**: 77-84.

Marx, SK and Kamber, BS (2010). "Trace-element systematics of sediments in the Murray–Darling Basin, Australia: Sediment provenance and palaeoclimate implications of fine scale chemical heterogeneity." Applied Geochemistry **25**: 1221-1237.

Tamar Estuary and Esk Rivers Program (2015). Tamar Estuary and Esk Rivers Catchments Water Quality Improvement Plan. T. NRM North. Launceston, NRM North.

Taylor, VF, Toms, A and Longerich, HP (2002). "Acid digestion of geological and environmental samples using open-vessel focused microwave digestion." Analytical and Bioanalytical Chemistry **372**: 360-365.

Yu, Z, Robinson, P, Townsend, A, Münker, C and Crawford, AJ (2000). "Determination of High Field Strength Elements, Rb, Sr, Mo, Sb, Cs, Tl and Bi at ng g^{-1} Levels in Geological Reference Materials by Magnetic Sector ICP-MS after $HF/HClO_4$ High Pressure Digestion." Geostandards Newsletter **24**(1): 39-50.

Chapter 6

Summary and conclusions

6.1 Results

The upper Tamar estuary, the location of the city of Launceston, is subject to flooding flows from the Esk Rivers, along with sedimentation that adversely affects recreation, scenic amenity and public health and exacerbates the flooding hazard, necessitating ongoing dredging or raking. In 2008, *WaterCAST* computer modeling of sediment flux to the Tamar estuary (BMT WBM Pty Ltd, 2010) found that river flows had increased by 50% and the rate of sedimentation of the estuary had increased by as much as 2.5 times that of pre-European settlement. The stimuli for the present study were questions arising in the community from the modeling results such as contemporary sedimentation rates and the land use associations with sediment flux as well as rates and causes of erosion relative to the previous "natural" or background status (Chapter 1).

WaterCAST modeling suggested that forestry and conservation lands, land uses dominant (48% of land area) in the upper Esk Rivers catchments, were the source of 64% of the sediment flux (BMT WBM Pty Ltd, 2008). However, this result was confounded by a climatic signal from these high altitude locations. Moreover, erosion hazard values used in the modeling were derived from a poor density of soil properties data and suspended sediment data, particularly in more remote parts of the region.

The findings of the research in Chapter 2 generally support the *WaterCAST* model's conclusions that the land use and climatic signals are confounded. Pre-historic sediment flux likely peaked during the Pleistocene-Holocene transition 11,000-8,000 years ago, comprised of a ready supply of highland sediments made available for fluvial transport by prior glacial and periglacial processes (Colhoun *et al.*, 2010; Fletcher & Thomas, 2010a). Subsequent to their arrival in Tasmania during the penultimate Pleistocene glacial period, Aborigines led a sedentary lifestyle in the humid west and southwest, where they used fire to provide resources for game and preventing climax of vegetation ecotypes to rainforest (Jackson, 1968; Jackson, 1999; Fletcher & Thomas, 2010a). The evidence also suggests some Aboriginal use of fire in the central highlands during arid glacial times, which could have contributed to aeolian erosion in central Tasmania and sedimentation further east, including the Esk Rivers basin (McIntosh *et al.*, 2009).

With the advent of the present interglacial, the Holocene epoch, Aborigines adopted a semi-sedentary lifestyle over wider rangelands. There is no evidence that Aborigines radiated into eastern Tasmania, including the study area, until the late (post-*Optimum*) Holocene (Lourandos, 1968). However, there is also no evidence of massive landscape scale engineering by fire in this region (Ellis, 1985). Aboriginal use of fire was not expansive, but limited to the maintenance of vegetation mosaic landscapes that provided temporal and spatial resource security over their rangelands.

Climate had been the dominant driver of landscape instability and erosion in the Esk Rivers basin during the late Holocene prior to British colonisation in 1803 (Macphail, 1979; Kirkpatrick & Bridle, 2007). However, with industrialisation, land use change became the dominant force in erosion, as elsewhere in the world. Successive waves of change or destabilisation precluded the establishment of new landscape equilibrium and enhanced erosion continued (Chapter 2). The otherwise global mid-20th century reversal of increased riverine silt flux due to interception of sediment by dams built on rivers

(Syvitski & Kettner, 2011) was not experienced in the Tamar estuary. The silt load of the Esk Rivers is so fine it passes across Trevallyn Dam and through the tailrace to the estuary before "salting out" (Foster *et al.*, 1986).

Since the 1970s, the most profound and extensive period of landscape destabilisation has coincided with a sustained reduction in precipitation (Kirkpatrick & Bridle, 2007). Landscape resilience has become threatened by increased El Niño Southern Oscillation (ENSO) frequency and the effects of anthropogenic climate change, including increasing frequency and severity of high precipitation storm events in the northeast highlands of the study catchment (White *et al.*, 2010). Efforts by land management authorities are concentrating on addressing erosion on farming and grazing lands and protection of agricultural capacity (Tamar Estuary and Esk Rivers Program, 2015).

The resolution of *WaterCAST* sediment flux modeling was constrained by the limited number of sediment rating stations upon which the model was based and low existing soil site density for erosion hazard assessment (Kidd *et al.*, 2015). If greater resolution in modeling could be achieved, based on improved field (erosion hazard or soils) data, erosion mitigation could be better targeted, especially in remote highland areas such as where the present study was conducted.

Sediment flux investigations have traditionally been by monitoring of erosion sites in catchments and, in more recent decades, by direct techniques such as "sediment chemical fingerprinting" (Davis & Fox, 2009). The work completed in the upper South Esk catchment in this project could form the basis for an integrated sediment fingerprinting study. Alternatively, should the project's soil data improve future erosion hazard calculations or if geological mapping was used as the basis for sediment flux modeling (e.g. *WaterCAST*), greater certainty in identification of erosion hotspots in this and other remote catchments could be achieved. These potential approaches would be more palatable as modeling on the basis of land use has inflamed political conflict over forestry and so become contentious in the community.

The methods and outcomes of the field and experimental work conducted in this project have been critically examined in Chapter 5. The pilot study area, >1,000 km^2 of the upper South Esk catchment, selected for soil sampling to validate geological mapping, included some of the greatest calculated erosion hazard values and modeled sediment flux values of the Tamar basin. Soils of the catchment were grouped into four types based upon their parent materials: basic igneous, acid igneous, sedimentary rocks and Quaternary sediments. As part of the sampling strategy, desktop sample stratification utilised a range of digital datasets to ensure adequate representation of the soils across a range of physiographic attributes in this complex catchment (Chapter 4). While land use (dominated by forestry) was found to be in a dynamic state not always consistent with digital land use data, *post hoc* validation across landscape attributes and successful statistical discrimination of the soil types confirmed the sampling strategy (Chapter 5).

Following mixed acid digestion of soil samples and elemental analysis by ICP-MS, a fingerprint of 13 elements that statistically distinguished the four soil types was identified. Of particular note is that most of the soil samples of the valley floors were able to be distinguished from their parent materials at higher altitude in the catchment, especially the sedimentary rock parent material that comprised 50% of the catchment. The nature of the reclassification of 14 out of 108 soil samples did not show a systematic relationship to organic matter content or environmental setting. Rather, it was those soil types that were expected to be confounded that were reclassified (soil types 3 and 4).

The hypothesis that soils of a pilot study catchment could be distinguished using geochemical “signatures” on the basis of simplified soil types has been confirmed. The field and laboratory work validated the available geological data at a sub-catchment scale in the pilot study area, excepting that statistical reclassification of some soils of types 3 (sedimentary parent rock) and 4 (Quaternary sediments) suggests likely limitations in distinguishing the boundaries between these soil types using geochemical characterisation. Any future investigation of the existing soil or surface geology mapping in the area should consider the possibility of poor resolution of boundaries between these soil types. The chemical characterisation would likely improve with greater density of sampling in soil types 3 and 4, although the fingerprint is unlikely to be able to accurately show the full extent of soil type 4 at its margins with other soil types. The new soils properties data collected will contribute to updated Tasmanian digital soils mapping (DSM) data in the dynamic *Soil and Landscape Grid of Australia* (SLGA) soils database (Kidd *et al.*, 2015).

The project has answered the research questions (pp 15-16) and fulfilled its aim (p 24), to facilitate better community and stakeholder engagement, decision making and outcomes in erosion management in the Tamar Basin catchments, towards more effective erosion control, reducing the rate of siltation in the Tamar Estuary.

6.2 Further work

New and efficient approaches to erosion management and sediment yield modeling are required in the context of human adaptation to environmental instability brought by the conjunct of rapid land use change and the anthropogenic climate change that is now upon us. The limitation on the reliability of computer-based modeling is the quality of the input data.

The methodology developed is applicable to other physiographically complex and remote areas of Tasmania, where remote sensing (e.g. LIDAR) will be increasingly important in improving on the SLGA soils database, Version 1. Application of the techniques developed in the present study for ground truthing of DSM and soil types classification has the potential to improve data inputs and SLGA product outputs from other data-poor regions of Tasmania. It is hoped and anticipated that with improvements in remote sensing, land use data will be more regularly updated, particularly before a subsequent erosion hazard model is built.

A greater number of sites could be sampled to better distinguish soil types 3 and 4, increasing the statistical certainty of the geochemical characterisation. Greater density of soil sampling and broader spread of sampling into minor geological units could be undertaken if required for contribution to the soil database. Systematic factors identified in sample reclassification should be used to improve sampling and analysis. The potential for intra-soil type discrimination and between soil-depths discrimination could be statistically tested using the *Kruskal-Wallis* test.

It is noteworthy that distinctive high field strength elements (HFSEs) were well recovered from granite soils by the soil digestion method used. While consideration could be given to improving the method for recovery of aluminium (Al) and rare earth elements (REE) from refractory granite-based materials, soil digestion methods should remain practical and efficient for use in regional laboratories.

Future sediment provenancing work could be undertaken in the wider catchment after Collins *et al*. (2017). This review by international experts allows full consideration of the constraints and opportunities raised by the present study. Traditional statistical ”unmixing” of a spatially and temporally representative sample of the suspended sediment at the catchment outlet could be used to test the chemical characterisation if required; a compound sample would optimally be representative of a typical water-year or typical (averaged) storm response hydrograph. However, if suspended sediment sampling and analysis were to occur, greater spatial resolution of sediment sources could be achieved by analysis of each stage of the storm hydrograph(s). This would provide for testing of the *WaterCAST* model and its land use attribution. Suspended sediment sampling and concentration, as trialed as part of this study's laboratory work, would be advisable instead of floodplain, dam or estuary sediment sinks for reasons well considered in the present work. However, such a study would be designed in the knowledge that opportunities to access river confluences are limited.

Fractionation and quantitation of the very fine (<20 μm, <10 μm) component of a representative suspended sediment sample of the Esk Rivers and comparison with Australian and global fine fractions would be useful for an improved understanding of the problem of apparently rapid siltation of the Tamar estuary due to the persistent fines fraction and may provide more information on climate control *versus* anthropogenic control of erosion and sedimentation. The significance of any contemporary resupply of fines in the sediment load by aeolian erosion could be informed by further analyses such as the chemical index of alteration (CIA analysis) and comparison with Australian studies, for example after Oliver *et al.* (1999). The possibility that the study catchment represents a non-equilibrium denudation region (McLennan, 1993), in delayed reaction to Pleistocene climatic destabilisation processes (Syvitski & Kettner, 2011) would thereby be tested.

The weighting of data inputs to *KLS* in calculation of erosion hazard should be considered at the time of soils data updates in view of soil properties documented during the present research. While estimation of the relative vulnerability of granite-based and sedimentary rock derived soils of the upper catchments to erosion was beyond the scope of the present study, the data collected should enhance improved assessment capacity towards sustainable soil management and land use including food production.

The erosion hazard mapping used in sediment flux modeling and in this study has taken the *land systems* approach to the next phase. Further innovation will enhance land capability assessment and should be used to guide revision of land use and/or management practices. Understanding the interactive roles of land use and past and present climatic influences in contemporary erosion and sediment flux processes in the study catchment should inform the efficient targeting of resources in erosion monitoring and in control measures important to adaptation to anthropogenic climate change.

6.3 References

BMT WBM Pty Ltd (2008). Review of Foster (1986) Report on Sedimentation Processes. Brisbane, BMT Group.

BMT WBM Pty Ltd (2010). Tamar Estuary and Esk Rivers Catchment WaterCAST Model: Final Report. Brisbane, BMT Group.

Colhoun, EA, Kiernan, K, Barrows, TT and Goede, A (2010). "Advances in Quaternary studies in Tasmania." Australian Landscapes, Special Publication 346, The Geological Society of London: 165-183.

Collins, A, Pulley, S, Foster, I, Gellis, A, Porto, P and Horowitz, A (2017). "Sediment source fingerprinting as an aid to catchment management: A review of the current state of knowledge and a methodological decision-tree for end-users." Journal of Environmental Management **194**: 86-108.

Davis, CM and Fox, JF (2009). "Sediment fingerprinting: Review of the Method and Future Improvements for Allocating Nonpoint Source Pollution." Journal of Environmental Engineering **135**(7): 490-504.

Ellis, EC (1985). "The relationships among eucalypt forest, grassland and rainforest in a highland area in north-eastern Tasmania." Australian Journal of Ecology **10**(3): 297-314.

Fletcher, M-S and Thomas, I (2010a). "The origin and temporal development of an ancient cultural landscape." Journal of Biogeography **37**: 2183–2196.

Foster, DN, Nittim, R and Walker, J (1986). Tamar River Siltation Study. Manly Vale, New South Wales, The University of New South Wales Water Research Laboratory.

Jackson, WD (1968). "Fire, air, water and earth- an elemental ecology of Tasmania." Proceedings of Ecological Society of Australia **3**: 6-16.

Jackson, WD (1999). "The Tasmanian legacy of Man and fire." Papers and Proceedings of the Royal Society of Tasmania **133**(1): 1-14.

Kidd, D, Webb, M, Malone, B, Minasny, B and McBratney, A (2015). "**Eighty-metre resolution 3D soil-attribute maps for Tasmania, Australia**." Soil Research **53**: 932-955.

Kirkpatrick, J and Bridle, K (2007). People, sheep and nature conservation: The Tasmanian experience. Collingwood, CSIRO Publishing.

Lourandos, H (1968). "Dispersal of activities : the east Tasmanian aboriginal sites." Papers and Proceedings of the Royal Society of Tasmania **102**(Part II): 41-46.

Macphail, MK (1979). "Vegetation and Climates in Southern Tasmania since the Last Glaciation." Quaternary Research **11**: 306-341.

McIntosh, PD, Price, DM, Eberhard, R and Slee, AJ (2009). "Late Quaternary erosion events in lowland and mid-altitude Tasmania in relation to climate change and first human arrival." Quaternary Science Reviews **28**: 850-872.

McLennan, SM (1993). "Weathering and global denudation." The Journal of Geology **101**: 295-303.

Oliver, RL, Hart, BT, Olley, J, Grace, M, Rees, C and Caitcheon, G (1999). The Darling River: Algal Growth and the Cycling and Sources of Nutrients. Murray-Darling Basin Commission Project M386, CRC for Freshwater Ecology; CSIRO Land and Water.

Syvitski, JPM and Kettner, A (2011). "Sediment flux and the Anthropcene." Philosophical transactions of the Royal Society **369**: 957-975.

Tamar Estuary and Esk Rivers Program (2015). Tamar Estuary and Esk Rivers Catchments Water Quality Improvement Plan. T. NRM North. Launceston, NRM North.

White, CJ, Grose, MR, Corney, SP, Bennett, JB, Holz, GK, Sanabria, LA, McInnes, KL, Cechet, RP, Gaynor, SM and Bindoff, NL (2010). Climate Futures for Tasmania: Extreme Events Technical Report. Hobart, The Antarctic Climate & Ecosystems Cooperative Research Centre.

Appendix 1

Spatial data sources, reliability and additional metadata

All data analysed and mapped for the present project used consistent projection and datum, GDA94 (Geocentric Datum of Australia (GDA) 1994, Map Grid of Australia (MGA) Zone 55), reprojected where necessary and georeferenced using the coastline of Tasmania. Positional accuracy in data layering of digitised paper maps for the present project is estimated to a nominal scale of 1:500,000.

The data varied in accuracy and reliability. Caveats on the use of each dataset are related to the currency of the data, to the available records and/or technology used to compile it (lineage) or to digital works in progress, subject to ongoing updates. There can be a high degree of confidence in the accuracy and reliability of recent digital data collection and mapping, given the generally large scales of the data sources and the purposes of use in this project. Therefore, data reliability limitations are primarily the age, quality and resolution of input data.

Tasmania raster base map image and vector base data: including coastline, town locations and the road network from *theLIST* (© State of Tasmania 2006) were provided by the University of Tasmania's Department of Geography and Environmental Studies as licensed by State government (Information & Land Services Division [ILS] of the Department of Primary Industries & Water [DPIW]).

Rivers (drainage network): Sourced from *CFEV Rivers* spatial data (scale 1:25,000), Conservation of Freshwater Ecosystems Values project, DPIW. Custodian: Land Information System Tasmania (LIST), Information & Land Services Division (ILS) of the Department of Primary Industries & Water (DPIW). Created by John Corbet, GIS Unit, ILS, DPIW, November 2004. Data were developed for the CFEV project by updating the LIST 1:25,000 data. Licensed to NRM North and used by permission of custodian.

River Section Catchments: Sourced from *CFEV River Section Catchments (RSCs)* (scale 1:25,000). Custodian: Water Resources Division (WRD), Department of Primary Industries and Water (DPIW). Created by John Corbett, GIS Unit, ILS, DPIW. Developed in several stages in conjunction with *CFEV rivers*; highly detailed sub-catchment subdivision of the state. Licensed to NRM North and used by permission of custodian. The data limitations of *CFEV* files relate to the resolution and scale of the input data: the digital elevation model (DEM) was built in 2004 from DPIW's Land Information System Tasmania (LIST) 1:25,000 scale 10 m contours, 1:25,000 river drainage network and 1:25,000 hydrographic theme. The 2003 *Fluvial Geomorphic Mosaics* dataset (integrated with CFEV) was developed by the Water Resources Division (WRD) of DPIW, mapped on a 200 m grid.

Pre-European vegetation data: Tasmanian data were sourced from the National Vegetation Information System (NVIS)- *Tas- Pre-European Vegetation* (Australian Natural Resources Atlas Data- Stage 1, Version 2) 2002, the Australian Government Department of the Environment, Water, Heritage and the Arts (custodian). The national data were collected by State agencies over several decades at scales of between 1;10,000 to 1,000,000, with Tasmania's data said to be of unspecified "finer scales." More detailed information is available on query of the layers. While each vegetation polygon may contain a mosaic of up to six vegetation types, only the dominant vegetation was used and seven broad vegetation categories were defined and mapped for this project. For the Tasmanian dataset, source data ranged from 1960 to 1997.

Cartography: *The Atlas of Tasmania* was the source of 1:1,800,000 scale cartography used for the 1964 vegetation analysis and presentation (Davies, 1964, in Davies, 1965) and land alienation analysis and presentation (Scott, 1965, in Davies, 1965). Accuracy is substantially limited by factors including the scale of the original paper maps, the methods used to collect data for those maps and polygon edge boundary and accuracy issues arising with digitisation. Tasmania's vegetation was mapped in six general types from aerial photography. The land alienation data for the original map was from A. McKay, 1962 (ed): *Journals of the Land Commissioners for Van Diemen's Land, 1826-28* and S.H. Roberts, 1924: *History of Australian Land Settlement (1788-1920)*.

Contemporary vegetation data: Tasmanian data were sourced from the *NVIS- Tas-Present Native Vegetation* (Australian Natural Resources Atlas Data- Stage 1, Version 2), 2001-02, compiled by the Department of Environment, Water, Heritage and Arts. Tasmanian data were supplied at 1:25,000 scale (caviat follows). Caveats applied by the custodian of the data are similar to those applied to the Pre-European dataset. Dominant vegetation types were mapped for the project although a single polygon may contain a mosaic of up to six vegetation associations. Detailed information is available in a related key layer containing boundaries of the source datasets. Tasmanian data source: *TASVEG, the Tasmanian Vegetation Map*. Custodian: Resource Management and Conservation, Tasmania, created by Tasmanian Vegetation Mapping Program (TVMP), DPIW, 2002; *TASVEG 2.0 Metadata*, Tasmanian Vegetation Mapping Program (TVMP), DPIW, 2009. The principal techniques used are aerial photographic interpretation, transformation of that data into digital form and incorporation of external data resources, such as the RFA, WHA and plantation mapping, followed by field verification. Generally 1:42,000 aerial photographs were used, although 1:15,000, 1:12,500 and 1:20,000 scale photographs were used where these were available. The most recent photographs were used where possible, usually post 1996. *TASVEG* will be revised in an ongoing fashion.

2001/02 land use data: Tasmanian digital data were provided by the Australian Bureau of Rural Sciences (BRS, Department of Agriculture, Fisheries and Forestry) 2006 publication, *2001/02 Land Use of Australia, Version 3*. In compiling the data product, non-agricultural land uses were based upon existing digital maps for protected areas (Department of Environment and Heritage 1:250,000 scale vector datasets, updated 2002; spatial errors 1-500 m), topographic features (Geoscience Australia 1:250,000 scale vector topographic maps, updated 2005; spatial errors <160 m for ≥90% data), tenures (BRS 250 m raster dataset compiled 1997; spatial errors up to 125 m) and forest (DEH 25 m raster data dated 2002 and GA 1988 data, 0.01 degree pixel size). Spatial errors do not exceed pixel size: 25 m for DEH data and <2 km for the GA data.

Other recent land use data: Plantation data were from BRS's Plantations 2001 dataset: no detailed metadata was provided, however the accuracy is stated to be high. Agricultural land use data sources were based on the Australian Bureau of Statistics' (ABS) agricultural censuses and surveys for the years mapped and incorporated BRS's "Land Use Mapping at Catchment Scale" project (2002). Spatial distribution of agricultural land uses was interpreted using Advanced Very High Resolution Radiometer (AVHRR) satellite imagery with ground control data. The accuracy of the specific agricultural land use allocations is variable; an available probability grid mapping dataset gives an indication of accuracy by allocation.

Tasmanian Land Use 2013: Created April 2016 at catchment scale through the Australian Collaborative Land Use and Management Program (ACLUMP) using standards set out in the 'Guidelines for land use mapping in Australia: principals, procedures and definitions, 4th edition 2011'. Land use is classified by its prime use using a hierarchical structure, Australian Land Use and Management Classification (ALUMC) v7, which allows attribution as broad classes to individual commodities to produce nationally consistent land use mapping. The land use mapping coverage is available for mixed dates at a scale that varies according to the intensity of land use activities and landscape context. Department of Primary Industries, Parks, Water and Environment (Natural Values Conservation Branch), Hobart.

Land Systems: *Land Systems of Tasmania*, Department of Primary Industries and Water (DPIW), Tasmania, 1978-1989. Metadata date: 2007. Custodian: Department of Primary Industries and Water (DPIW). Non-unique land systems were developed based on six descriptor classes. Within each land system, land components are described which present examples of soil and vegetation variation across topographic sequences proportion estimates, but unmapped boundaries). Regions were mapped separately in seven regions and amalgamated to form a digital statewide coverage: Region 1: King Island; Region 2: Flinders Island; Region 3: North; Region 4: North East; Region 5: Central Plateau; Region 6: South, East and Midlands; Region 7: South West. Aerial photography (1:42,000) was interpreted for soil, vegetation and topography, along with use of existing soil and geological maps, based on field sites (~2,800) recording soil and vegetation descriptions. Land Systems are considered to have a nominal scale of 1:100,000.

Surface geology 1:500,000 (500k): *1:500,000 Scale Digital Geology of Tasmania*, ©Crown in Right of Tasmania, custodian Mineral Resources Tasmania (undated). A statewide dataset derived from the 1:250,000 scale *Digital Geology of Tasmania*. Rock units have been grouped and boundaries have been generalised for 1:500,000 scale.

Surface geology 1:25,000 (25k): *1:25,000 Scale Digital Geology of Tasmania*, ©Crown in Right of Tasmania, custodian Mineral Resources Tasmania. Beginning April 2008, in progress/continual development to cover the state. This dataset is derived from geological reports, 1:25,000, 1:50,000 and 1:63,360 scale mapping, new field mapping and interpretation of aerial photography and airborne geophysical data. It has been compiled to fit the *Land Information System Tasmania* (LIST) digital topographic base.

Erosion hazard data (Tasmania): The National Soil Attribute Maps (Version 1) were developed between 2011-2015 by the Soil and Landscape Grid of Australia. In Tasmania the soil attributes were modeled using decision trees with piecewise linear models using local scale input data and covariates. Collaborators may be found on the website: http://www.clw.csiro.au/aclep/soilandlandscapegrid/ProductDetails-SoilAttributes.html#SoilAttributeProductDetails An erosion hazard index (1-100) was developed from the Tasmania product using the revised universal soil loss equation (RUSLE) KLS component (erodibility potential (or hazard) based on soil properties (SOC%, clay, sand, silt, stones, permeability and structure size) and slope length and slope gradient. Resolution: 80 m. Developer: Darren Kidd (2016) Department Primary Industries, Parks, Water and Environment.

Appendix 2

Key to geologic unit codes

Example format = Trxy

1. T = unit age. Two letters may be used for units spanning for than one age period.
Cainozoic Cz
Quaternary Q
Tertiary T
Mesozoic Mz
Cretaceous K
Jurassic J
Triassic -R
Palaeozoic Pz
Permian P
Carboniferous C
Devonian D
Silurian S
Ordovician O
Cambrian -C
Proterozoic -P
Neoproterozoic N
Mesoproterozoic M
Palaeoproterozoic L
Archaean A

2. r = gross rock descriptor. A one letter code to reflect the broad lithological composition of the unit
IGNEOUS EXAMPLES
g felsic to intermediate intrusive granite, granodiorite, tonalite, monzonite, diorite, syenite
d mafic intrusive gabbro, dolerite, norite
f felsic extrusive / high level intrusive rhyolite, dacite, ignimbrite, pyroclastic rocks
a intermediate extrusive / high level intrusive andesite, trachyte, latite, pyroclastic rocks
b mafic extrusive / high level intrusive basalt, scoria, shoshonite, pyroclastic rocks
u ultramafic undivided (intrusive & extrusive) komatiite, high Mg basalt, pyroxenite, dunite, wehrlite
k alkaline ultramafic kimberlite, lamprophyre, carbonatite
SEDIMENTARY
s siliciclastic/undifferentiated sediment shale, siltstone, sandstone, conglomerate, mudstone

j volcanogenic sediment epiclastic sediments and breccias, greywacke, arkose
l carbonate sediment limestone, marl, dolomite
c non-carbonate chemical sediment chert, evaporite, phosphorite, BIF
o organic-rich rock coal, amber, oil shale
MIXED SEDIMENTARY & IGNEOUS
v felsic & mafic volcanics
i felsic & mafic intrusives
w volcanics & sediments
METAMORPHIC
y low-medium grade meta clastic sediment slate, phyllite, schist, quartzite
t low-medium grade metabasite mafic schist, greenstone, amphibolite
r low-medium grade metafelsite rhyolitic schist, meta-andesite
m calc-silicate and marble meta carbonates and calcareous sediments
n high grade metamorphic rock gneiss, granulite, migmatite
p high-P metamorphic rock eclogite, blueschist
h contact metamorphic rock hornfels, spotted slate
e metamorphosed ultramafic rocks serpentinite, talc schist, chlorite schist (no feldspars), tremolite schist, ultramafic amphibolite
OTHER
z fault / shear rock mylonite, fault breccia, cataclasite, gouge
q vein quartz vein, carbonate vein
x complex, undivided, unknown mélange

3. xy = One or two letters to reflect the stratigraphic name of a unit. Where practical, these letters reflect stratigraphic grouping or hierarchy. For instance, formations within a named group should have letter symbols reflecting their parent group.
eg: Manning Group - Psm
Colraine Mudstone - Psmc
Echo Hills Formation - Psme

Reference:

Whitaker, A.J., Raymond, O.L., Liu, S., Champion, D.C., Stewart, A.J., Retter, A.J., Percival, D.S., Connolly, D.P., Phillips, D.M., Hanna, A.L. (2006): Surface geology of Australia 1:1,000,000 scale, eastern States [Digital Dataset] Canberra: The Commonwealth of Australia, Geoscience Australia, sourced 2009. <http://www.ga.gov.au>

Appendix 3: Soil and site descriptions (continued overleaf).

Site	Geo code (500k)	Geo code (25k)	Land system	Elevation (m a.s.l.)	Soil profile	Topsoil	Subsoil	Site description
S1.3	Qrc	Qptd	772451	915	Gradational	O: 0-3 cm; A: 3-12 cm; black-brown silty organic soil between stones	B: 12-30 cm (cont's between stones); v. dk brown clayey silt, worms throughout	*E. dalrympleana* dry sclerophyll open-forest; ferny ground cover
S1.4	Qrc	Qptd	772451	842	Gradational	A: 0-4 cm; med reddish-brown loam	B: 4-(?) cm; orange-brown silty clay; 50% stones	Regrowth *E. delegatensis* over *Leptospermum* dry sclerophyll forest
S1.7	Jdtm	Jd	472343	864	Gradational	O: 0-3 cm; very dk brown-black organic-rich. A: 3-13 cm; dark red-brown clayey loam	B1 (E): 13-17 cm; bleached orange light clay. B2: 17-25 cm (cont.'s); stony, heavier dark brown loamy clay	*E. delegatensis* 5-15 y.o. regrowth (partial canopy retention)
S1.8	Jdtm	Jd	572351	616	Gradational	A: 0-12 cm; organic-rich black loam	B: 12-30 cm; black loamy clay interstitially between stones	*E. delegatensis* dry sclerophyll open-forest
S1.9	Qrc	Qptd	572341	724	Duplex; small stones	A: 0-12 cm; dk chocolate-brown organic-rich clayey loam	B: 12-28 cm; orange-brown light clay with small stones. C: 28-35 cm (cont's); orange-brown clay with angular stones	*E. obliqua* & *E. viminalis* dry sclerophyll open-forest regrowth (remnant stems). Was wet *E. obliqua* forest with broadleaf shrubs (as mapped 2008)
S1.10	Qrc	Qptd	572341	916	Gradational	A: 0-12 cm; red-brown clayey, slightly gritty loam	B: 12-90 cm (cont's); orange clayey silt; angular to subangular stones all sizes to 10x12x15 cm	*E. delegatensis* multi-storey open-forest; biodiverse with broadleaf shrubs
S1.11	Qrc	Qptd	572242	481	Duplex; stony	A: 0-10 cm; mid orange-brown clayey loam	B1: 10-25 cm; orange-brown gritty clay. B2: 25-35 cm (cont.'s) orange-brown clay, orange-grey mottles	*E. amygdalina* dry sclerophyll open-forest
S1.13	Jdtm	Jd	572341	1071	Duplex; soil pocket among dolerite columns at base of outcrop	O: 0-1 cm; A: 1-24 cm; black-brown organic rich clayey loam; angular stones	B: 24-45 cm (cont's, but more stones); orange-brown light clay; angular stones. B-C 45 cm; weathering rock	Alpine *E. delegatensis* dry sclerophyll forest >70% canopy but with some gaps; varied understorey; leaf litter abundant
S1.14	Qrc	Qptd	472253	467	Gradational	A: 0-10 cm; dark orange-brown loamy clay	B: 10-30 cm (cont's); orange-brown clay with increasing stoniness (angular to subangular dolerite)	Degraded grassy woodland to dry sclerophyll forest; *E. pauciflora*, *E. obliqua* and *E. amygdalina*; *A. dealbata* understorey; sedges and native grasses groundcover
S2.1	Dgrt	Dgaap	641341	604	Gradational	A: 0-8 cm; dk greyish-br loamy sand	B: 8-21 cm; slightly paler grey-brown sand	Sparse regrowth, mixed spp./eucalypt forest
S2.2	Dgrt	Dgaap	641341	845	Gradational, stony, gritty, no structure	A: 0-16 cm; black sand with organic mat	B: 16-41 cm; v. dk brown sand	Dense regrowth, was wet *E. delegatensis* forest over rainforest
S2.3	Dgrt	Dgaap	641341	885	Gradational, roots throughout; structureless except at base	A: 0-21 cm; med. Brown-grey gritty sand	B: 21-46 cm; grey sand grading to orange brown gritty sand with some clay	Oldgrowth *E. delegatensis* dry sclerophyl
S2.4	Dgrt	Dgae	641341	676	Gradational, coarse grit throughout	A: 0-16 cm; dk grey-brown gritty loam	B: 16-48 cm; grading from A to dk brown clayey sand	Acacia-dominated regrowth, was wet *E. obliqua* forest with broadleaf shrubs
S2.5	Dgrh	Dgnv	641341	794	Duplex	A: 0-20 cm; dk brown slightly sandy loam	B: 12-45 cm; (cont's); orange-brown silty clay	Alpine *Leptospermum* scrub and *Poa* grassland
S2.6	Dgrh	Dgnv	641341	842	Gradational	A: 0-10 cm; dark reddish-brown sandy loam	B: 10-35 cm; red-brown sandy clay with grit	Eucalypt regrowth; was wet *E. dalrympleana* forest
S2.7	Dgrh	Dgnx	641341	827	Gradational	A: 0-5 cm; dk/ mid brown sandy loam	B: 5- 28 cm; mid orange-brown clayey silt	Eucalypt regrowth; was wet *E. dalrympleana* forest
S2.9	Dgrr	Dgne	641341	782	Gradational, gravelly & small stones throughout	A: 0-13 cm; v. dk brown silty loam, lots rootlets, some gritty white sand	B: 13-30 cm; very dk brown silty sand, some rootlets	Acacia-dominated regrowth, was wet *E. obliqua* forest with broadleaf shrubs
S2.10	Dgrr	Dgne	641341	413	Duplex colour, gradational texture	A: 0-7 cm; very dark sandy matrix with coarse white sand	E: 7-9 cm; bleached horizon. B: 9-35 cm, pale orange-brown sandy with a little clay	*E. amygdalina* dry sclerophyll native open-forest/woodland
S2.11	Dgrr	Dgne	641341	802	Duplex	A: 0-18 cm; dk brown loam	B: 18-40 cm; orange-brown compacted gritty clayey silt	*E. delegatensis, E viminalis, A. dealbata* wet forest regrowth, ferny understorey
S3.4	Psp	Plb	664321	828	Gradational	A: 0-2 cm; black peaty	B: 2-40 (cont's?); compacted heavy clay, mottled orange and grey with rounded to sub-rounded clasts	Buttongrass plain margin with *Leptospermum* scrub
S3.6	Psp	Plb	664321	814	Duplex	A: 0-18 cm; black organic sandy loam	B: 18-43 cm (cont's); very dk grey-brown gritty silt; water seeping	Alpine moor/buttongrass plain; *Leptospermum, E. rodwayii* copses
S3.7	Psp	Plb	664321	825	Gradational	O: 0-2 cm; leaf mould. A: 2-10 cm; dk grey-brown sandy silt	B: 10-30 cm; dk grey-brown gritty sandy silt	Dry sclerophyll woodland, *Leptospermum* understorey
S3.8	Psp	Pus	464122	260	Duplex	A: 0-17 cm; dk grey-brown loamy sand	B1: 17-27 cm; pale grey-brown loamy sand. B2: 27-36 cm (cont's); compacted pale orange-brown clayey sand with many small stones	Improved pasture
S3.9	Psp	Pfs	564242	315	Duplex	A: 0-8 cm; dk brown sandy silt	B: 8-48 cm (cont's); uniform yellow silty sand with few stones	*E. amygdalina* dry sclerophyll open-forest; small clearing with good understorey cover
S3.10	ODsm	ODq	554231	264	Strongly duplex; shallow	A: 0-16 cm; dk brown silty loam	B: 16-26 cm; pale yellow silty clay (lots of rock fragments). C: 26 cm; weathering sedimentary rock	Improved pasture; eucalypt regrowth to NW; pine/euc regrowth to SE
S3.11	ODsm	ODqp	464131	295	Duplex	A: 0-3 cm; light beige-brown loamy clay	B: 3-45 cm; yellow-reddish pale brown clay with grits; C: shaly stone at 45 cm	Second rotation pine plantation
S3.12	ODsm	ODq	493125	496	Gradational	A: 0-3 cm; black-brown sandy loam	B1: 3-18 cm; dk grey-brown sandy loam. B2: 18-23 cm; grey clayey loam with grits. C: 23-28 cm (cont's); mottled yellow-orange clay	Remnant degraded *E. seiberi* open-forest, no understorey, canopy trees only. Acting firebreak for pine plantation.
S3.13	ODsm	ODq	553241	597	Gradational/uniform	A: 0-3 cm; very dk brown silty sand, very stony: flaky, angular stones	B: 3-30 cm (bigger stones; cont's); mid-grey sand, a little silt	Dry sclerophyll forest *E. seiberi, E amygdalina*, fringing recent forestry coup

Appendix 3: Soil and site descriptions (continued).

Site	Geo code (500k)	Geo code (25k)	Land system	Elevation (m a.s.l.)	Soil profile	Topsoil	Subsoil	Site description
S3.14	ODsm	ODq	493125	813	Duplex	A: 0-8 cm; dk brown clayey silt	B: 8-33 cm (to large stone); orange-brown silty clay; flaky stones throughout	Dry sclerophyll open-forest (70% canopy); *E. amygdalina, E. delegatensis* & *E. dalrympleana*
S3.15	ODsm	ODqp	493125	438	Gradational	A: 0-4 cm; black-brown sandy loam	B: 4-22 cm; grey loamy sand with angular rock. C: 22 cm (cont's); yellow sandy clay and weathering rocks	Burnt-out 2nd rotation pine plantation
S3.16	ODsm	ODqp	664321	801	Gradational	A: 0-8 (?) cm; black peaty	B: 8 (?)-26 cm; grading to grey clay at B-C boundary; C: 26 cm, into shaly regolith	Low wooded hillock, recently logged eucalypt forest
S3.17	ODsm	ODqp	493125	370	Duplex	A: 0-8 cm; light grey silty	B: 8-28 cm; v. pale orange-brown silty clay with charcoal and rock fragments throughout	Pine plantation 2nd rotation established
S3.18	ODsm	ODqp	553241	551	Duplex	A: 0-3 cm; very dk brown silty loam with grit	B1: 3-12 cm; hard, pale grey clay with orange stones/nodules. B2: 12-21 cm; very compacted pale orange and grey mottled clay. C: 21-25 cm (cont's); pale orange-grey regolith	Regrowth *E. amygdalina* dry sclerophyll forest
S3.19	ODsm	ODqm	493125	491	Gradational; very stony	A: 0-3 cm; dark orange-brown clayey loam	B: 3-29 cm; mid to dark orange-brown loamy clay. C: 29-32 cm (cont's); regolith fragments in orange mottled clay	2nd rotation pine plantation ~3 y.o.; SW aspect
S3.20	ODsm	ODqm	553241	646	Gradational; very stony (angular)	A: 0-10 cm; dark grey-brown sandy loam	B: 10-28 cm; grey clayey loam. C: 28 cm (cont's); loamy grey clay and angular stones	Regenerating *E. obliqua*, subdominant *E. viminalis* forest; understorey mostly bracken. Little regeneration; almost clearfelled. Was wet *E. obliqua* forest over broadleaf shrubs.
S3.21	ODsm	ODqm	554231	439	Duplex; lots small stones	A: 0-18 cm; brown clayey loam	B: 18-30 cm (cont.'s); orange-red clay, compacted	*E. delegatensis* 20 y.o. regrowth wet forest
S3.22	ODsm	ODqm	554231	614	Gradational, very stony	A: 0-13 cm; dark brown organic-rich sandy loam	B: 13-28 cm; mid-pale brown clayey loam. C: 28 cm (cont's); loamy light brown clay	*E. delegatensis, E. viminalis* subdominant medium forest >70% canopy, dry sclerophyll forest
S3.23	ODsm	ODqm	664321	817	Gradational; deep; stones, quartz and yellow shale	A: 0-15 cm; dk brown silty loam	B: 15-50 cm; mid-brown silty clay loam to loamy clay	Heavily cleared mixed forest regrowth; much woody debris
S3.26	Psp	Pfs	464321	654	Gradational	A: 0-5 cm; mid yellow-brown sandy loam with charcoal	B1: 5-23 cm; brown-grey sandy clay loam; B2: 23-37 cm; pale brown-grey clayey sand; C: 37-44 cm (cont's); saturated mottled grey to orange clayey sand; reddish stone nodules	In remnant stand of dry sclerophyll forest; *E. delegatensis* dominant, *E. amygdalina* sub-dominant, sags and scant shrubby understorey; leaf litter
S4.3	Qa	Qha	493125	362	Gradational; riverstones, sand, silt	A: 0-2 cm; dark sandy soil	B: 2-25 cm; dark coarse sandy; rootlets; compacted	Riparian remnant *Leptospermum* scrub in agricultural land
S4.4	Qa	Qha	493125	335	Gradational, sand content increasing with depth	A: 0-12 cm; v. dark brown light loam	B: 12-40 cm, v. dk brown, micaceous appearance near base	Open riparian vegetation; some native shrubs, pasture spp. & blackberries
S4.5	Qa	Qha	493125	290	Gradational	A: 0-22 cm; brown silty sand	B: 22-55 cm (cont's); pale grey-brown silty sand; becomes grittier with depth	In *E. nitens* plantation, first rotation from improved pasture, river flats
S4.6	Qa	Qha	393121	226	Gradational	A: 0-27 cm; dk grey-brown silty loam, some sand; no worms	B: 27-43 cm (cont's); dk grey-brown silty clay, very hard at 43 cm; no stones, few worms, thick weed root sward.	Improved pasture with hawthorn hedges; broad alluvial flats
S4.7	Qa	Qha	493125	268	Gradational	A: 0-22 cm; dark reddish-brown clayey loam	B: 22-43 cm (cont's); red-yellowish clayey loam	*E. nitens*, first rotation from improved pasture, 12-15 y.o.
S4.8	Qa	Qha	493125	250	Gradational	A: 0-12 cm; mid-grey sandy loam; some fine sand	B1: 12-28 cm; paler grey loamy silt; some fine sand. B2: 28-38 cm (cont's); pale grey silty clay; oxidising stones; some fine sand	*E. nitens*, first rotation from improved pasture, 4-5 y.o.; 250 m onto river flat from woody hillock
S4.9	Qrc	Qha	464122	258	Duplex/gradational	A: 0-21 cm; grey-brown slightly sandy loam	B1: 21-35 cm; mid-yellow-brown sandy clay-loam. B2: 35-50 cm (cont's); pale yellow-brown compacted sandy loam; orange-brown regolith nodules	Improved pasture; within hayshed enclosure inside cropped paddock
S4.11	Qrc	Qha	464122	258	Gradational	A: 0-20 cm; brown loam.	B1: 20-39 cm; pale brown-grey slightly sandy silty loam. B2: 39-50 cm (cont's); pale yellowy-grey slightly sandy silty clay-loam	Improved pasture; paddock cropped for forage; sample around remnant tree where soil not ploughed
S4.12	Qrc	Qha	464122	248	Gradational; deep	A: 0-18 cm; very dk brown clayey loam	B1: 18-32 cm; very dk grey loamy clay. B2: 32-52 cm (cont.'s); very dk grey heavy clay	Improved pasture, thick grass sward
S4.13	Qa	Qpao	641341	370	Gradational	A: 0-2 cm; dk brown sandy loam, organic matter	B: 2-17 cm; dk brown silty loam	Riparian regrowth (mapped as *E. regnans*, 2008); old terrace above river
S4.14	Qa	Qpao	464122	273	Duplex; deep alluvial soil	A: 0-31 cm; dk brown silty sand	B1 (E): 31-41 cm; light br-grey sand. B2: 41 cm (cont.s); heavy orange-grey mottled clay	Improved pasture, relatively poorly drained; rushes (*Juncus*?)
S4.15	Qa	Qpao	493125	271	Gradational	A: 0-13 cm; yellow-brown sandy loam	B: 13-32 cm (cont's); compacted pale yellow clayey sand	Degraded scrub. *E. amygdalina* remnants, *A. dealbata* regrowth, sedgy understorey. Sample in copse of *A. dealbata*
S4.16	Qa	Qpao	553241	312	Duplex, too gritty to dig far	A: 0-10 cm; br-black loam, very friable	B1: 10-23 cm; pale grey to slightly yellowish-grey with depth; silty fine sand with grits; oxidising rock fragments. B2: 23-35 cm (cont's); orange light clay, gritty not stony.	Dry sclerophyll forest *E. amygdalina, E. viminalis*, thinned, little understorey; old terrace above river
S4.18	Qa	Qpao	464122	243	Gradational	A: 0-8 cm; grey-brown sandy loam	B: 8-28 cm (cont's); very pale yellowish grey sandy loam; some nodules; very compacted and too hard to dig further with spade.	Improved pasture; wide stock corridor on farm.
S4.19	Qa	Qpao	464122	249	Duplex; deep alluvial soil	A: 0-28 cm; dk br sandy silt	B1 (E): 28-40 cm; pale br-grey sand with brown mottles & small round stone. B2: 40-50 cm (cont.'s); light orange heavy clay	Improved pasture, 100 m west of mature tall pine hedge

Appendix 4

Land systems codes.

Code	First digit	Second digit	Third digit	Fourth digit	Fifth digit	Sixth digit
Numeral	Climate-mean rainfall p.a. (mm)	Geological age of surface materials	Surface rock or sediment	Average altitude of land system (m)	Land forms	Unique land system number[a]
0	N/A	Precambrian (metamorphosed)	N/A	N/A	N/A	N/A
1	375-500	Precambrian (unmetamorphosed)	Acid igneous	0-300	Flat plains	
2	500-625	Cambrian	Basic igneous	300-600	Undulating hills	
3	625-750	Ordovician	Sedimentary siliceous	600-900	Low hills (<100 m)	
4	750-1000	Silurian Devonian	Sedimentary argillaceous	900-1200	Hills (100-300 m)	
5	1000-1250	Lower Devonian-Tremadocian Cambrian (Mathinna beds)	Sedimentary calcareous	1200-1500	Mountains (300+ m)	
6	1250-1500	Carboniferous		1500-1800	Coastal dunes and beaches	
7	1500-2000	Permian Triassic Jurassic				
8	2000-2500	Tertiary				
9	2500+	Quaternary				

[a]Used to identify discrete land systems, having the first five digits the same, but which are still separable, generally because of differences in the soils and vegetation.

Source: Department of Primary Industries and Water (2007): *Land Systems of Tasmania*.

Appendix 5: Process blanks elemental concentration data, method detection limits (MDL), limits of quantitation (LOQ) and Central Science Laboratory instrument blanks (sample equivalent; mg/kg).

Batch (process blanks)	Batch 1 (n=3)		Batch 2 (n=3)		Batch 3 (n=3)		Batch 4 (n=2)		Overall (N=11)		Calculated from process blanks		Central Science Laboratory instrument blanks[a]	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	MDL (SD*3)	LOQ (SD*10)	Mean CSL	SD
Al	23.0	2.06	20.1	4.96	18.8	1.27	32.8	28.0	22.8	10.1	30.2	101	13.5	6.37
Sc	0.0107	0.00466	0.0691	0.0116	0.0527	0.0310	0.0230	0.0100	0.0403	0.0278	0.083	0.278	0.0953	0.0916
Ti	0.823	0.305	0.715	0.324	0.936	0.558	1.68	0.587	0.980	0.489	1.47	4.89	0.391	0.348
V	0.280	0.0537	0.0950	0.0150	0.154	0.0281	0.103	0.0125	0.163	0.0799	0.240	0.799	0.320	0.210
Cr	0.130	0.0716	0.428	0.0709	0.299	0.0890	0.126	0.0512	0.257	0.140	0.419	1.40	0.123	0.075
Mn	0.410	0.170	0.560	0.211	0.491	0.168	0.292	0.111	0.452	0.168	0.505	1.68	0.345	0.213
Fe	6.15	1.16	10.9	2.98	7.63	1.84	5.33	0.590	7.70	2.64	7.91	26.4	3.46	1.04
Co	0.0773	0.0174	0.182	0.0335	0.336	0.226	0.0581	0.0256	0.173	0.147	0.442	1.47	0.121	0.0824
Cu	0.733	0.172	1.16	0.0570	2.65	0.750	0.640	0.154	1.36	0.883	2.65	8.83	0.714	0.421
Zn	3.26	1.20	2.19	0.636	2.81	0.427	2.92	1.13	2.78	0.804	2.41	8.04	1.88	0.997
Rb	0.0546	0.0109	0.340	0.0225	0.227	0.0138	0.0510	0.0268	0.179	0.123	0.369	1.23	0.369	0.384
Sr	0.533	0.184	0.260	0.0277	0.756	0.242	0.414	0.0490	0.498	0.229	0.686	2.29	0.533	0.202
Y	0.0127	0.00415	0.0332	0.00512	0.0294	0.00412	0.0440	0.0114	0.0285	0.0119	0.0357	0.119	0.0557	0.0626
Zr	0.0853	0.00899	0.0319	0.00539	0.0367	0.00936	0.0370	0.00134	0.0487	0.0233	0.0698	0.233	0.0689	0.0763
Nb	0.512	0.0381	0.0465	0.00300	0.0541	0.00364	0.0830	0.0182	0.182	0.203	0.610	2.03	0.283	0.297
Mo	0.697	0.0674	0.334	0.0581	0.351	0.101	2.20	0.533	0.777	0.708	2.12	7.08	4.43	6.37
Cd	0.0393	0.0185	0.0319	0.0161	0.0167	0.0147	0.0871	0.0271	0.0398	0.0280	0.0840	0.280	0.0562	0.0825
Sn	0.666	0.115	0.486	0.0408	0.473	0.0148	0.416	0.00193	0.519	0.107	0.321	1.07	0.706	0.296
Sb	0.0746	0.0252	0.0631	0.00311	0.0193	0.0127	0.0640	0.00580	0.0545	0.0252	0.0755	0.252	0.177	0.137
Cs	0.0207	0.00115	0.0983	0.0114	0.0694	0.00746	0.0150	0.00428	0.0541	0.0349	0.105	0.349	0.145	0.133
Ba	0.976	0.118	0.399	0.0311	0.764	0.144	0.850	0.196	0.738	0.244	0.731	2.44	1.06	0.445
La	0.0326	0.0223	0.0153	0.00117	0.0187	0.00112	0.0110	0.00139	0.0202	0.0125	0.0374	0.125	0.0252	0.0265
Ce	0.0833	0.0120	0.0126	0.00303	0.0227	0.00111	0.0160	0.00280	0.0353	0.0301	0.0904	0.301	0.0637	0.0906
Pr	0.159	0.0230	0.0193	0.00118	0.0154	0.00307	0.0190	0.00137	0.0563	0.0638	0.191	0.638	0.225	0.469
Nd	0.145	0.0328	0.0232	0.0144	0.0260	0.00399	0.0260	0.00289	0.0578	0.0557	0.167	0.557	0.979	2.507
Sm	0.0267	0.0151	0.0232	0.0135	0.0307	0.0135	0.0180	0.00845	0.0253	0.0116	0.0347	0.116	0.0358	0.0270
Eu	0.0340	0.00795	0.0352	0.00622	0.0447	0.00599	0.0320	0.00290	0.0369	0.00706	0.0212	0.0706	0.0577	0.0299
Gd	0.0313	0.0181	0.0365	0.00491	0.0334	0.0101	0.0370	0.0127	0.0343	0.0101	0.0304	0.101	0.0657	0.0260
Tb	0.0240	0.0156	0.0146	0.00225	0.0140	0.00201	0.0130	0.00422	0.0167	0.00822	0.0247	0.0822	0.0317	0.0274
Dy	0.0253	0.0216	0.0166	0.00225	0.0154	0.00306	0.0290	0.00701	0.0209	0.0111	0.0332	0.111	0.0312	0.0226
Ho	0.0193	0.0163	0.0153	0.00308	0.0160	0.00343	0.0190	0.00137	0.0173	0.00744	0.0223	0.0744	0.0288	0.0297
Er	0.0207	0.0099	0.0319	0.00859	0.0227	0.00639	0.0280	0.0114	0.0256	0.00843	0.0253	0.0843	0.0362	0.0310
Tm	0.0213	0.0162	0.0193	0.00463	0.0174	0.00310	0.0210	0.00137	0.0196	0.00747	0.0224	0.0747	0.0337	0.0304
Yb	0.0233	0.0150	0.0345	0.00634	0.0341	0.00725	0.0470	0.0100	0.0336	0.0113	0.0340	0.113	0.0523	0.0298
Lu	0.0206	0.0102	0.0246	0.00298	0.0287	0.00125	0.0250	0.00147	0.0247	0.00548	0.0164	0.0548	0.0420	0.0404
Hf	0.0273	0.00943	0.0146	0.00466	0.0100	0.00197	0.0280	0.0141	0.0193	0.0100	0.0299	0.100	0.0507	0.0613
Tl	0.00800	0.00203	0.0219	0.00397	0.0120	0.00530	0.0490	0.00414	0.0204	0.0149	0.0446	0.149	0.113	0.199
Pb	0.207	0.146	0.196	0.100	0.153	0.0335	0.166	0.00813	0.182	0.0800	0.240	0.800	0.128	0.0779
Bi	0.237	0.0190	0.101	0.00841	0.0874	0.0206	0.0890	0.00971	0.132	0.0657	0.197	0.657	0.563	0.638
Th	0.00133	0.00116	0.00199	0.00199	0.00133	0.00115	0.00500	0.00143	0.00218	0.00180	0.00540	0.0180	0.0246	0.0589
U	0.00333	0.00230	0.00333	0.00305	0.00334	0.00115	0.00300	0.00142	0.00327	0.00176	0.00528	0.0176	0.0325	0.0523

[a]REE method: N= 12; "other" method: N=20

Appendix 6a: Basic igneous SRM BHVO2 measured elemental concentration data (mg/kg).

Batch no.	1	1	1	Batch 1		2	2	2	Batch 2		3	3	3	Batch 3		Overall			
Tube ID	7	8	9	Average	RSD (%)	7	8	9	Average	RSD (%)	7	8	9	Average	RSD (%)	Average	RSD (%)	Pub. values	Recovery (%)
Al	60900	60000	62300	61100	2	62500	56600	60700	59900	5	63500	62900	64500	63600	1	61500	4	71400	86
Sc	26.3	25.7	26.9	26.3	2	28.4	27.2	28.5	28.0	3	30.1	29.2	29.8	29.7	2	28.0	5	32	88
Ti	15700	15700	15900	15800	1	15600	15300	15500	15500	1	15600	15100	15300	15300	1	15500	1	16300	95
V	313	317	322	317	1	315	309	314	313	1	314	315	322	317	1	316	1	317	100
Cr	291	280	288	286	2	283	280	288	284	1	281	272	280	278	2	282	2	280	101
Mn	1275	1271	1276	1274	0	1238	1247	1283	1256	2	1250	1221	1253	1241	1	1257	2	1317	95
Fe	80200	79500	80700	80100	1	78800	76800	80500	78700	2	78500	77600	78100	78100	1	79000	2	86300	92
Co	45.5	43.9	44.9	44.8	2	44.3	43.2	45.7	44.4	3	43.4	41.9	44.4	43.2	3	44.1	3	45	98
Cu	127	123	126	125	2	124	126	130	127	2	124	124	129	126	2	126	2	127	99
Zn	98.6	103	105	102	3	98.9	102	105	102	3	95.3	93.5	92.0	93.6	2	99.2	5	103	96
Rb	8.53	8.18	8.36	8.36	2	8.42	7.81	8.14	8.12	4	8.80	8.45	8.67	8.64	2	8.37	3	9.11	92
Sr	375	367	376	373	1	378	360	379	372	3	384	386	391	387	1	377	2	396	95
Y	21.1	20.6	21.7	21.1	3	22.4	20.0	22.3	21.6	6	23.5	23.5	24.5	23.8	2	22.2	6	26	85
Zr	163	162	164	163	1	162	159	165	162	2	162	164	165	163	1	163	1	172	95
Nb	17.1	16.6	17.4	17.0	2	17.1	16.8	17.8	17.2	3	16.8	17.2	17.3	17.1	1	17.1	2	18.1	95
Mo	4.05	3.54	3.7	3.76	7	4.43	4.07	3.88	4.13	7	4.09	3.48	3.28	3.61	12	3.83	9	4	96
Cd	0.182	0.218	0.213	0.205	10	0.191	0.126	0.256	0.191	34	0.0957	0.177	0.106	0.126	35	0.174	29	0.06	290
Sn	5.12	1.55	1.78	2.82	71	1.78	1.64	1.59	1.67	6	1.75	1.68	1.89	1.77	6	2.09	52	1.7	123
Sb	5.38E-02	1.45E-02	-4.81E-03	2.12E-02	122	0.137	0.137	0.127	0.134	4	0.110	0.101	0.101	0.104	5	8.63E-02	56	0.13	67
Cs	8.00E-02	7.84E-02	6.63E-02	7.49E-02	10	1.38E-03	-6.22E-03	-5.87E-04	-1.81E-03	173	5.47E-02	4.52E-02	7.19E-02	5.73E-02	24	4.35E-02	74	0.1	44
Ba	129	123	126	126	2	126	123	128	126	2	128	127	129	128	1	127	2	131	97
La	14.1	14.5	15.2	14.6	4	15.0	14.0	14.9	14.6	4	15.1	15.0	15.4	15.2	1	14.8	3	15.2	97
Ce	37.1	36.5	37.9	37.1	2	36.4	35.1	37.4	36.3	3	36.4	36.9	37.3	36.9	1	36.8	2	37.5	98
Pr	4.7	4.74	5.13	4.86	5	5.14	4.86	5.23	5.07	4	5.11	5.25	5.16	5.17	1	5.03	4	5.35	94
Nd	22.7	22.5	22.6	22.6	0	23.1	22.6	24.2	23.3	4	23.7	23.9	24.7	24.1	2	23.3	3	24.5	95
Sm	5.54	5.46	5.55	5.52	1	5.71	5.58	5.89	5.73	3	5.98	6.04	6.24	6.09	2	5.78	4	6.07	95
Eu	1.87	1.88	2.00	1.92	4	1.95	1.80	2.02	1.92	6	1.95	1.98	2.04	1.99	2	1.94	4	2.07	94
Gd	5.23	4.99	5.34	5.19	4	5.33	5.21	5.72	5.42	5	5.38	5.63	5.62	5.54	2	5.38	4	6.24	86
Tb	0.82	0.83	0.9	0.85	5	0.88	0.83	0.89	0.87	3	0.92	0.94	0.93	0.93	1	0.88	5	0.92	96
Dy	4.70	4.78	5.08	4.85	4	4.98	4.87	5.21	5.02	3	5.12	5.24	5.26	5.20	1	5.03	4	5.31	95
Ho	0.825	0.845	0.933	0.868	7	0.920	0.893	1.016	0.943	7	0.937	0.965	0.985	0.962	2	0.924	6	0.98	94
Er	2.17	2.09	2.37	2.21	7	2.37	2.15	2.58	2.37	9	2.5	2.47	2.77	2.58	7	2.39	9	2.54	94
Tm	0.239	0.246	0.300	0.262	13	0.312	0.286	0.325	0.308	6	0.297	0.309	0.311	0.306	3	0.292	10	0.33	88
Yb	1.74	1.68	1.74	1.72	2	1.79	1.74	1.81	1.78	2	1.96	1.95	2.02	1.98	2	1.83	6	2	91
Lu	0.199	0.179	0.253	0.210	18	0.257	0.213	0.249	0.240	10	0.245	0.258	0.244	0.249	3	0.233	12	0.274	85
Hf	4.68	4.62	4.93	4.74	3	4.29	4.23	4.43	4.32	2	4.04	4.35	4.39	4.26	5	4.44	6	4.36	102
Tl	1.41E-02	6.43E-03	1.06E-02	1.04E-02	37	1.69E-02	4.53E-04	1.28E-02	1.00E-02	85	2.08E-02	1.80E-02	1.92E-02	1.93E-02	7	1.32E-02	47		
Pb	1.98	1.73	1.75	1.82	8	1.80	1.55	1.62	1.66	8	1.61	1.60	1.65	1.62	2	1.70	7	1.6	106
Bi	1.25E-01	5.93E-02	7.20E-02	8.53E-02	41	2.41E-02	-8.01E-03	-8.36E-03	2.57E-03	173	6.67E-03	-3.15E-03	-2.38E-02	-6.77E-03	428	2.70E-02	134		
Th	1.23	1.10	1.15	1.16	5	1.16	1.11	1.26	1.18	7	1.14	1.26	1.31	1.23	7	1.19	6	1.22	98
U	0.448	0.441	0.429	0.439	2	0.395	0.432	0.461	0.430	8	0.400	0.420	0.416	0.412	2	0.427	5	0.403	106

Appendix 6b: Granite SRM AC-E measured elemental concentration data (mg/kg).

Batch no.	1	1	1	Batch 1		2	2	2	Batch 2		3	3	3	Batch 3		Overall			
Tube ID	1	2	3	Average	RSD (%)	1	2	3	Average	RSD (%)	7	8	9	Average	RSD (%)	Average	RSD (%)	SRM values	Recovery (%)
Al	30300	37100	38900	35500	13	12800	15800	13700	14100	11	23800	26900	24900	25200	6	24900	36	77800	32
Sc[a]	1.48	1.25	1.56	1.43	11	1.30	1.39	1.33	1.34	3	1.46	1.24	1.30	1.33	9	1.37	8	0.11	1243[a]
Ti	677	595	677	650	7	537	585	567	563	4	578	581	589	583	1	598	8	595	101
V	0.00E+00	0.00E+00	4.95E-02	1.65E-02	173	5.42E-02	1.40E-02	4.46E-02	3.76E-02	56	1.87E-02	8.50E-03	8.55E-03	1.19E-02	49	2.20E-02	92	3	1
Cr	0.779	0.884	0.913	0.859	8	0.985	0.302	1.262	0.850	58	0.596	0.679	1.510	0.928	54	0.879	38	3.4	26
Mn	416	348	433	399	11	344	378	364	362	5	373	364	385	374	3	379	7	449	84
Fe	16400	15600	17200	16400	5	14500	15400	15400	15100	3	14900	14800	15100	14900	1	15500	5	17350	89
Co	3.81E-02	5.35E-02	1.05E-01	6.56E-02	54	6.04E-02	9.53E-02	1.05E-01	8.70E-02	27	4.53E-02	1.53E-01	0.00E+00	6.62E-02	119	7.29E-02	59	0.2	36
Cu	2.94	3.14	2.79	2.96	6	8.10	2.80	2.42	4.44	72	4.38	5.34	3.05	4.26	27	3.88	44	4	97
Zn	221	204	247	224	9	303	215	208	242	22	209	216	205	210	3	225	13	224	101
Rb	129	82	130	114	24	84.2	94.9	93.4	90.8	6	94.9	99.8	97.9	97.5	3	101	16	152	66
Sr	0.765	0.003	0.980	0.583	88	0.488	0.441	0.310	0.413	22	0.391	1.121	0.353	0.622	70	0.539	62	3	18
Y	29.7	13.2	36.1	26.3	45	11.8	16.3	11.8	13.3	20	22.8	27.8	22.0	24.2	13	21.3	38	184	12
Zr	800	753	843	799	6	676	761	749	729	6	742	738	747	742	1	757	6	780	97
Nb	107	99.0	116	107	8	76.1	91.6	85.5	84.4	9	86.7	97.7	91.3	91.9	6	94.6	12	110	86
Mo	1.92	1.65	1.91	1.83	8	2.93	1.88	1.95	2.25	26	1.95	1.81	1.84	1.86	4	1.98	17	2.5	79
Cd	0.770	0.860	0.797	0.809	6	0.746	0.632	0.819	0.732	13	0.697	0.574	0.724	0.665	12	0.735	12	0.61	121
Sn	16.0	14.7	16.9	15.9	7	13.7	15.3	14.8	14.6	5	14.8	14.8	15.0	14.9	1	15.1	6	13	116
Sb	0.342	0.285	0.272	0.300	12	0.396	0.224	0.304	0.308	28	0.299	0.353	0.403	0.352	15	0.320	17	0.4	80
Cs	2.24	2.41	2.40	2.35	4	1.47	1.64	1.66	1.59	7	1.58	1.49	1.77	1.61	9	1.85	20	3	62
Ba	44.7	11.8	50.4	35.7	58	39.3	42.8	41.4	41.2	4	45.2	43.7	45.6	44.8	2	40.6	26	55	74
La	11.7	1.32	12.4	8.47	73	6.74	9.65	8.30	8.23	18	11.9	11.0	12.0	11.6	5	9.44	36	59	16
Ce	47.8	4.3	44.5	32.2	75	28.4	36.9	35.3	33.6	13	42.9	38.4	40.7	40.7	6	35.5	34	154	23
Pr	4.97	0.43	5.51	3.64	77	2.68	3.66	3.14	3.16	15	4.76	4.63	4.82	4.74	2	3.85	39	22.2	17
Nd	21.1	3.3	24.4	16.3	70	11.0	14.7	12.3	12.7	15	19.9	20.1	20.2	20.0	1	16.3	38	92	18
Sm	5.47	1.17	6.48	4.38	65	2.68	3.58	3.06	3.11	14	4.94	4.94	4.80	4.90	2	4.13	37	24.2	17
Eu	0.443	0.080	0.453	0.325	65	0.178	0.249	0.200	0.209	17	0.340	0.329	0.294	0.321	8	0.285	40	2	14
Gd	4.84	1.41	6.02	4.09	58	2.16	2.85	2.41	2.47	14	4.02	4.58	3.92	4.18	9	3.58	39	26	14
Tb	1.03	0.340	1.20	0.857	53	0.452	0.618	0.467	0.512	18	0.801	0.935	0.804	0.847	9	0.739	37	4.8	15
Dy	6.24	2.76	7.96	5.65	47	2.99	3.94	3.07	3.33	16	5.47	6.68	5.69	5.95	11	4.98	35	29	17
Ho	1.36	0.612	1.59	1.19	43	0.636	0.828	0.631	0.699	16	1.14	1.38	1.15	1.22	11	1.04	34	6.5	16
Er	4.00	2.18	4.96	3.71	38	1.87	2.46	2.01	2.11	15	3.40	4.31	3.49	3.73	13	3.18	33	17.7	18
Tm	0.662	0.316	0.783	0.587	41	0.296	0.433	0.324	0.351	21	0.517	0.674	0.557	0.583	14	0.507	33	2.6	19
Yb	4.20	2.57	5.25	4.01	34	2.28	2.77	2.16	2.40	14	3.73	4.68	3.80	4.07	13	3.49	30	17.4	20
Lu	0.583	0.328	0.668	0.526	34	0.299	0.377	0.300	0.325	14	0.501	0.629	0.580	0.570	11	0.474	30	2.45	19
Hf	25.6	25.3	30.1	27.0	10	24.4	27.0	25.0	25.5	5	26.6	25.0	24.7	25.4	4	26.0	6	27.9	93
Tl	0.834	0.789	0.953	0.859	10	0.814	0.898	0.840	0.850	5	0.883	0.874	0.807	0.855	5	0.855	6	0.9	95
Pb	33.9	34.0	38.9	35.6	8	35.6	37.1	36.3	36.3	2	36.5	36.6	38.0	37.0	2	36.3	4	39	93
Bi	0.187	0.092	0.211	0.163	38	0.141	0.128	0.190	0.153	22	0.144	0.142	0.133	0.140	4	0.152	23	0.4	38
Th	9.03	3.18	11.60	7.93	54	7.17	9.28	8.38	8.27	13	9.15	9.78	8.54	9.16	7	8.46	26	18.5	46
U	4.09	2.00	4.82	3.64	40	4.13	4.56	4.58	4.42	6	4.31	4.13	4.14	4.19	2	4.08	19	4.6	89

[a]See Addendum, overleaf.

Appendix 6c: Soil SRM NIST2711a measured elemental concentration data (mg/kg).

Batch no.	1	1	1	Batch 1		2	2	Batch 2		3	3	3	Batch 3		4	4	4	Batch 4		Overall			
Tube ID	7	8	9	Average	RSD (%)	7	8	Average	RSD (%)	7	8	9	Average	RSD (%)	7	8	9	Average	RSD (%)	Average	RSD (%)	SRM values	Recovery (%)
Al	58400	51000	55000	54800	7	48900	52800	50800	5	49000	38600	50400	46000	14	42700	42600	39700	41700	4	48100	13	67200	72
Sc	8.05	6.72	7.50	7.42	9	7.78	8.22	8.00	4	7.63	6.19	7.39	7.07	11	7.22	7.96	6.93	7.37	7	7.42	8	8.5	87
Ti	3010	2740	2840	2860	5	2880	3040	2960	4	2940	2710	2810	2820	4	3010	3000	2850	2950	3	2890	4	3170	91
V	79.6	71.4	74.6	75.2	5	75.2	78.9	77.0	3	79.2	76.9	75.5	77.2	2	77.1	75.8	74.5	75.8	2	76.2	3	80.7	94
Cr	45.5	41.5	42.9	43.3	5	45.2	45.1	45.1	0	44.4	43.1	42.8	43.4	2	45.8	43.9	43.2	44.3	3	43.9	3	52.3	84
Mn	631	583	609	608	4	586	619	603	4	583	571	583	579	1	628	611	597	612	3	600	3	675	89
Fe	27200	24400	26000	25900	5	25500	26700	26100	3	25500	25000	24600	25100	2	26200	26300	25600	26000	1	25700	3	28200	91
Co	9.49	8.53	9.15	9.06	5	8.89	9.30	9.10	3	10.38	9.84	8.87	9.70	8	10.27	9.94	9.65	9.95	3	9.48	6	9.89	96
Cu	130	123	127	127	2	128	138	133	6	138	137	131	135	3	131	132	133	132	1	132	3	140	94
Zn	404	375	383	387	4	379	383	381	1	370	371	343	361	4	376	383	349	369	5	374	4	414	90
Rb	76.0	66.0	76.8	72.9	8	56.1	61.2	58.7	6	78.5	63.7	73.7	72.0	10	57.3	59.6	53.2	56.7	6	65.7	13	120	55
Sr	203	178	202	195	7	164	180	172	7	171	139	185	165	14	169	167	159	165	3	174	10	242	72
Y	21.3	17.0	20.8	19.7	12	15.9	15.8	15.8	1	19.3	16.2	18.4	18.0	9	15.7	16.2	15.2	15.7	3	17.4	12		
Zr	109	95.0	104	103	6	112	110	111	1	107	102	103	104	2	103	110	105	106	3	105	4		
Nb	18.3	16.6	17.7	17.5	5	18.5	18.8	18.6	1	18.0	15.2	17.9	17.0	9	19.0	18.8	17.8	18.5	4	17.9	6		
Mo	1.58	1.16	1.54	1.43	16	1.67	1.85	1.76	8	1.60	1.29	1.55	1.48	11	1.61	1.01	1.19	1.27	24	1.46	17		
Cd	52.2	46.7	52.3	50.42	6	49.8	51.9	50.9	3	51.5	49.1	49.9	50.2	2	51.2	51.0	48.4	50.2	3	50.4	3	54.1	93
Sn	4.59	4.44	4.26	4.43	4	4.48	4.98	4.73	8	4.37	3.27	4.53	4.05	17	4.53	4.37	4.56	4.49	2	4.40	9		
Sb	24.9	22.6	23.9	23.8	5	23.7	24.6	24.1	2	22.5	19.8	22.9	21.8	8	25.1	24.1	23.4	24.2	3	23.4	6	23.8	98
Cs	5.63	5.08	5.61	5.44	6	4.94	4.81	4.87	2	5.31	4.26	4.60	4.72	11	3.61	4.54	4.29	4.14	12	4.79	12	6.7	71
Ba	686	616	663	655	6	644	691	668	5	658	575	662	632	8	641	649	633	641	1	647	5	730	89
La	22.1	18.1	24.6	21.6	15	15.1	14.8	14.9	2	21.0	17.6	19.5	19.4	9	14.0	15.4	13.5	14.3	7	17.8	19	38	47
Ce	48.1	40.3	52.1	46.9	13	33.1	32.8	32.9	0	42.8	36.8	41.1	40.2	8	32.2	34.3	30.3	32.3	6	38.5	17	70	55
Pr	5.66	4.81	6.19	5.55	12	4.13	4.22	4.17	2	5.25	4.50	5.19	4.98	8	4.05	4.32	4.08	4.15	4	4.76	14		
Nd	22.3	19.1	24.4	21.9	12	16.0	16.5	16.2	2	20.3	17.1	19.6	19.0	9	16.4	17.7	15.9	16.6	6	18.7	14	29	64
Sm	4.36	3.92	4.96	4.42	12	3.26	3.62	3.44	8	4.06	3.30	3.82	3.73	11	3.68	3.88	3.54	3.70	5	3.85	12	5.93	65
Eu	0.742	0.659	0.865	0.755	14	0.572	0.629	0.600	7	0.658	0.571	0.682	0.637	9	0.716	0.607	0.628	0.650	9	0.666	12	1.1	61
Gd	3.55	3.20	3.99	3.58	11	2.97	3.02	2.99	1	3.41	2.90	3.13	3.15	8	2.88	3.00	3.08	2.99	3	3.19	10	5	64
Tb	0.617	0.531	0.668	0.605	11	0.506	0.520	0.513	2	0.599	0.461	0.557	0.539	13	0.513	0.525	0.521	0.520	1	0.547	10	0.8	68
Dy	3.96	3.55	4.15	3.89	8	3.29	3.49	3.39	4	3.53	3.02	3.41	3.32	8	3.30	3.40	3.43	3.38	2	3.50	9	5	70
Ho	0.748	0.696	0.820	0.754	8	0.713	0.684	0.699	3	0.708	0.587	0.661	0.652	9	0.680	0.666	0.673	0.673	1	0.694	8		
Er	2.19	2.12	2.45	2.26	8	2.09	2.11	2.10	1	2.12	1.72	2.07	1.97	11	2.04	1.92	2.00	1.99	3	2.08	8		
Tm	0.333	0.295	0.357	0.328	10	0.334	0.333	0.334	0	0.311	0.273	0.333	0.306	10	0.284	0.300	0.313	0.299	5	0.315	8		
Yb	2.34	2.12	2.44	2.30	7	2.25	2.15	2.20	3	2.34	1.84	2.24	2.14	12	2.29	2.23	2.19	2.24	2	2.22	7		
Lu	0.311	0.308	0.334	0.318	4	0.293	0.304	0.299	3	0.349	0.276	0.315	0.313	12	0.286	0.358	0.336	0.327	11	0.315	8	0.5	63
Hf	3.66	3.47	3.72	3.62	3	3.41	3.19	3.30	5	3.38	2.90	3.34	3.20	8	3.32	3.98	3.51	3.60	9	3.44	8	9.2	37
Tl	2.70	2.72	2.94	2.78	5	2.69	2.76	2.73	2	2.56	2.46	2.49	2.51	2	1.54	1.70	1.69	1.64	5	2.39	20	3	80
Pb	1410	1310	1430	1380	5	1310	1370	1340	3	1310	1250	1280	1280	2	1340	1370	1310	1340	2	1340	4	1405	95
Bi	1.24	1.29	1.36	1.30	5	1.62	1.78	1.70	7	1.57	1.61	1.67	1.61	3	1.87	1.92	1.79	1.86	4	1.61	14		
Th	12.3	11.0	13.0	12.1	8	10.4	11.0	10.7	4	9.72	8.87	9.59	9.39	5	10.3	11.7	10.3	10.8	8	10.7	11	15	72
U	2.84	2.58	2.95	2.79	7	2.31	2.40	2.36	3	2.30	2.07	2.33	2.23	6	2.38	2.40	2.36	2.38	1	2.45	10	3.01	81

Appendix 6b addendum

Published and measured values for scandium in the geological reference material AC-E

Source[1]	Method	Result (mg/kg)	Uncertainty
Govandaraju (1994)	Recommended compiled value	0.11	SD=0.3
Govandaraju (1995)	Recommended compiled value (N=25)	0.11	0.05 conf. limit
Korotev *et al.* (1996)	Powdered sub-sample sealed in tube; INAA	0.1	95% conf. limit (rel)
El Maghraoui *et al.* (1999)	Fusion; XRF & INAA	0.112	SD=0.008
Yu *et al.* (2001)	Acid digestion; sector field ICP-MS	0.916	RSD=4.31%
Eggins (2003)	Fusion; LA ICP-MS	1.0	±0.1 uncertainty
Bayon *et al.* (2009)	Fusion digestion; ICP-MS	0.9	SD=0.1
This study	Acid digestion; sector field ICP-MS (N=9)	1.37	RSD=8%

[1]Refer online database *GeoReM* <http://georem.mpch-mainz.gwdg.de/sample_query_pref.asp> (Max Planck Institute, Version 14, 04/01/2012).

Appendix 7a: Soil type 1 replicates measured elemental concentration data (mg/kg) (continued overleaf).

Geo code (500k)	Qrc																				
Geo code (25k)	Qptd																				
Batch	1	4	4	4	Batch 4		Overall		1	1	1	Batch 1		1	4	4	4	Batch 4		Overall	
Tube ID	10	16	17	18					18	19	20			21	22	23	24				
Sample ID	1.4 sub	1.4 sub	1.4 sub	1.4 sub	Average	RSD (%)	Average	RSD (%)	1.11 sub	1.11 sub	1.11 sub	Average	RSD (%)	1.11 top	1.11 top	1.11 top	1.11 top	Average	RSD (%)	Average	RSD (%)
Al	45900	22000	28100	29600	26600	15	31400	33	48600	44400	46100	46300	5	32200	18000	20500	12400	16900	25	20800	40
Sc	14.5	8.82	10.9	11.9	10.5	15	11.5	20	16.1	13.9	13.7	14.6	9	6.50	4.62	5.70	3.32	4.55	26	5.04	27
Ti	4290	4190	4340	3960	4170	5	4200	4	10500	10000	10100	10200	2	10800	10700	10600	9170	10200	9	10300	8
V	172	171	172	167	170	2	170	1	219	215	223	219	2	137	139	144	126	136	7	137	5
Cr	140	147	145	141	144	2	143	2	88.7	85.7	85.6	86.7	2	49.5	50.6	52.4	48.0	50.3	4	50.1	4
Mn	680	692	710	704	702	1	697	2	646	614	649	636	3	1306	1325	1320	1244	1296	4	1299	3
Fe	45700	47200	49100	47400	47900	2	47300	3	60400	57900	59500	59300	2	36662	38500	40400	36400	38400	5	38000	5
Co	22.4	23.2	23.8	24.0	23.6	2	23.3	3	63.3	61.3	64.1	62.9	2	48.5	51.4	54.7	50.2	52.1	4	51.2	5
Cu	27.6	30.4	31.6	26.0	29.3	10	28.9	9	57.7	57.3	56.4	57.1	1	32.5	40.3	39.0	35.7	38.3	6	36.9	9
Zn	80.2	73.9	84.2	74.3	77.5	8	78.2	6	58.7	53.3	60.4	57.5	6	51.6	48.3	50.1	46.2	48.2	4	49.1	5
Rb	8.04	1.81	2.47	3.53	2.60	33	3.96	71	29.4	30.1	32.6	30.7	5	38.5	28.4	35.6	23.4	29.1	21	31.5	22
Sr	43.2	23.5	32.2	37.8	31.2	23	34.2	25	31.4	27.4	28.7	29.2	7	35.0	23.8	27.1	16.3	22.4	25	25.6	30
Y	7.10	1.88	2.80	3.37	2.68	28	3.79	61	3.56	2.10	3.34	3.00	26	2.31	1.05	2.17	0.884	1.37	51	1.60	46
Zr	159	154	158	150	154	3	155	3	228	231	235	231	2	245	265	272	230	256	9	253	8
Nb	9.96	9.67	10.0	9.64	9.77	2	9.82	2	14.6	14.1	14.5	14.4	2	16.1	16.9	16.8	13.2	15.6	14	15.7	11
Mo	1.77	0.720	0.787	0.552	0.687	18	0.958	58	0.313	2.68E-02	-8.40E-03	0.111	160	0.243	-0.921	3.54	1.31	1.31	170	1.04	182
Cd	0.146	9.50E-02	0.124	6.52E-02	9.46E-02	31	0.107	33	0.113	0.180	0.201	0.165	28	0.143	1.04E-02	8.16E-02	8.70E-02	5.97E-02	72	8.06E-02	68
Sn	2.96	2.90	3.24	2.79	2.98	8	2.97	6	1.76	1.76	1.78	1.77	1	1.70	1.65	1.64	1.40	1.56	9	1.60	8
Sb	0.361	0.422	0.413	0.355	0.397	9	0.388	9	0.134	0.172	0.221	0.176	25	0.135	0.254	0.226	0.210	0.230	10	0.206	25
Cs	4.02	1.54	2.14	2.68	2.12	27	2.60	41	0.568	0.528	0.706	0.601	16	1.03	0.493	0.884	0.408	0.595	43	0.703	43
Ba	164	101	126	145	124	18	134	20	275	261	304	280	8	362	314	395	290	333	16	340	14
La	8.70	1.65	2.71	3.03	2.46	29	4.02	79	4.17	3.33	5.44	4.31	25	3.48	2.33	3.16	1.83	2.44	27	2.70	28
Ce	20.9	4.67	7.39	8.31	6.79	28	10.3	70	10.6	8.68	13.5	10.9	22	9.01	5.96	7.42	4.23	5.87	27	6.66	31
Pr	3.46	0.637	1.01	1.08	0.908	26	1.55	83	0.915	0.610	1.13	0.884	29	0.667	0.628	0.882	0.499	0.670	29	0.669	24
Nd	10.7	2.79	4.18	4.53	3.83	24	5.54	63	4.54	3.31	5.41	4.42	24	3.44	2.29	3.24	1.85	2.46	29	2.70	28
Sm	3.36	0.634	1.04	1.13	0.933	28	1.54	80	0.869	0.620	1.00	0.830	23	0.697	0.372	0.756	0.296	0.475	52	0.530	43
Eu	1.66	8.41E-02	0.127	0.169	0.127	33	0.511	151	0.191	0.113	0.191	0.165	27	8.50E-02	6.29E-02	0.125	3.48E-02	7.42E-02	62	7.69E-02	49
Gd	2.72	0.461	0.709	0.930	0.700	33	1.21	85	0.670	0.449	0.685	0.601	22	0.523	0.277	0.458	0.215	0.317	40	0.368	40
Tb	1.59	9.06E-02	0.152	0.166	0.136	30	0.500	146	0.110	4.78E-02	0.0973	8.50E-02	39	6.94E-02	4.54E-02	7.98E-02	4.41E-02	5.65E-02	36	5.97E-02	30
Dy	3.30	0.617	0.972	1.21	0.932	32	1.52	79	0.897	0.541	0.846	0.762	25	0.664	0.293	0.561	0.205	0.353	53	0.431	50
Ho	1.54	0.120	0.170	0.235	0.175	33	0.515	132	0.151	9.02E-02	0.139	0.127	25	8.55E-02	5.69E-02	0.116	4.60E-02	7.30E-02	52	7.61E-02	41
Er	2.25	0.419	0.534	0.748	0.567	29	0.987	86	0.579	0.333	0.523	0.478	27	0.380	0.228	0.351	0.133	0.237	46	0.273	42
Tm	1.28	4.75E-02	7.06E-02	0.103	7.36E-02	38	0.376	161	6.07E-02	1.86E-02	4.74E-02	4.22E-02	51	1.50E-02	9.02E-03	3.36E-02	3.01E-03	1.52E-02	107	1.52E-02	87
Yb	2.36	0.485	0.686	0.802	0.657	24	1.08	79	0.708	0.477	0.586	0.590	20	0.438	0.206	0.363	0.155	0.241	45	0.291	46
Lu	1.33	6.58E-02	9.10E-02	0.125	9.39E-02	32	0.404	154	5.38E-02	3.31E-02	4.05E-02	4.25E-02	25	2.18E-02	2.76E-02	5.38E-02	9.28E-03	3.02E-02	74	2.81E-02	67
Hf	4.76	4.63	4.50	4.62	4.59	2	4.63	2	6.29	6.39	6.54	6.41	2	6.57	7.72	7.67	6.31	7.23	11	7.07	10
Tl	0.437	0.219	0.208	0.210	0.212	3	0.268	42	0.483	0.468	0.499	0.483	3	0.557	0.329	0.686	0.522	0.513	35	0.524	28
Pb	13.8	14.3	14.3	14.0	14.2	1	14.1	2	12.7	12.5	13.2	12.8	3	16.1	17.7	19.2	16.4	17.8	8	17.3	8
Bi	0.529	0.193	0.175	0.146	0.171	14	0.261	69	6.57E-02	4.76E-02	5.33E-02	5.55E-02	17	4.62E-02	2.21E-04	0.481	0.220	0.234	103	0.187	117
Th	5.84	2.40	3.71	4.08	3.40	26	4.01	35	3.96	3.54	4.49	4.00	12	2.77	2.37	2.36	1.68	2.14	18	2.30	20
U	2.18	1.95	2.07	2.04	2.02	3	2.06	5	1.73	1.70	1.86	1.76	5	1.63	1.70	1.79	1.65	1.71	4	1.69	4

Appendix 7a: Soil type 1 soil replicates measured elemental concentration data (mg/kg) (continued).

Geo code (500k)	Jdtm							
Geo code (25k)	Jd							
Batch	1	4	4	4	Batch 4		Overall	
Tube ID	12	19	20	21				
Sample ID	1.7 sub	1.7 sub	1.7 sub	1.7 sub	Average	RSD (%)	Average	RSD (%)
Al	46000	31900	26300	24800	27700	14	32300	30
Sc	11.7	9.92	7.40	8.24	8.52	15	9.33	21
Ti	6610	6030	6150	6230	6140	2	6260	4
V	240	220	223	223	222	1	227	4
Cr	46.2	42.8	41.6	42.9	42.4	2	43.4	5
Mn	1910	1810	1770	1760	1780	1	1810	4
Fe	76300	74700	74300	76000	75000	1	75300	1
Co	40.4	40.7	38.8	40.1	39.9	2	40.0	2
Cu	84.3	82.7	86.3	86.5	85.1	3	84.9	2
Zn	81.6	76.6	73.5	71.1	73.7	4	75.7	6
Rb	1.91	2.92	1.42	2.37	2.24	34	2.16	30
Sr	15.2	12.5	11.5	9.7	11.2	13	12.2	19
Y	3.51	2.10	1.73	1.47	1.77	18	2.20	41
Zr	121	113	119	116	116	2	117	3
Nb	9.57	8.82	9.64	9.28	9.24	4	9.32	4
Mo	0.739	-0.348	-0.490	-0.471	-0.436	-18	-0.143	-415
Cd	0.176	0.151	-2.65E-02	5.17E-02	5.89E-02	151	8.83E-02	106
Sn	2.01	1.82	2.33	1.64	1.93	19	1.95	15
Sb	0.151	0.260	0.127	0.048	0.145	74	0.147	60
Cs	0.704	0.566	0.546	0.460	0.524	11	0.569	18
Ba	89.8	95.8	90.2	100	95.3	5	94.0	5
La	3.37	3.32	2.16	2.14	2.54	27	2.75	25
Ce	8.08	7.77	5.18	5.03	5.99	26	6.52	25
Pr	0.724	0.894	0.642	0.626	0.720	21	0.721	17
Nd	3.59	3.57	2.60	2.65	2.94	18	3.10	18
Sm	0.903	0.755	0.515	0.559	0.610	21	0.683	26
Eu	0.261	0.146	0.120	7.12E-02	0.112	34	0.150	54
Gd	0.838	0.537	0.405	0.386	0.443	19	0.542	38
Tb	0.207	9.91E-02	7.05E-02	6.42E-02	7.80E-02	24	0.110	60
Dy	1.053	0.663	0.513	0.448	0.541	20	0.669	41
Ho	0.269	0.102	9.08E-02	7.30E-02	8.86E-02	17	0.134	68
Er	0.669	0.404	0.326	0.272	0.334	20	0.418	42
Tm	0.154	3.09E-02	2.60E-02	2.20E-02	2.63E-02	17	5.83E-02	110
Yb	0.644	0.275	0.246	0.306	0.276	11	0.368	50
Lu	0.146	3.94E-02	2.64E-02	2.81E-02	3.13E-02	23	5.99E-02	96
Hf	3.54	3.21	3.41	3.47	3.36	4	3.41	4
Tl	0.258	0.117	0.120	0.102	0.113	8	0.149	49
Pb	11.6	11.4	11.8	11.9	11.7	2	11.7	2
Bi	0.367	0.109	9.57E-02	0.101	0.102	7	0.168	79
Th	2.16	1.90	1.52	1.65	1.69	11	1.81	16
U	1.50	1.54	1.51	1.53	1.53	1	1.52	1

Appendix 7b: Soil type 2 soil replicates measured elemental concentration data (mg/kg) (continued overleaf).

Geo code (500k)	Dgrt							Dgrh															
Geo code (25k)	Dgaap							Dgnv															
Batch	1	4	4	Batch 4		Overall		1	4	4	4	Batch 4		Overall		1	4	4	4	Batch 4		Overall	
Tube ID	25	4	6					28	7	8	8					29	10	11	12				
Sample ID	2.1 top	2.1 top	2.1 top	Average	RSD (%)	Average	RSD (%)	2.5 sub	2.5 sub	2.5 sub	2.5 sub	Average	RSD (%)	Average	RSD (%)	2.5 top	2.5 top	2.5 top	2.5 top	Average	RSD (%)	Average	RSD (%)
Al	56100	30000	30000	30000	0	38700	39	85200	45200	55400	67000	55900	20	63200	27	66900	30000	30800	28000	29600	5	38900	48
Sc	3.12	2.06	2.24	2.15	6	2.47	23	7.80	5.22	5.90	8.14	6.42	24	6.77	21	5.47	2.94	3.68	3.46	3.36	11	3.89	28
Ti	3430	3090	3040	3060	1	3190	7	6580	6710	6290	6210	6400	4	6450	4	6510	5980	5520	5700	5740	4	5930	7
V	30.9	27.8	27.1	27.4	2	28.6	7	94.5	97.8	93.9	96.3	96.0	2	95.6	2	82.5	76.7	76.1	76.6	76.5	0	78.0	4
Cr	10.3	9.65	8.96	9.31	5	9.63	7	52.2	51.8	49.2	48.9	49.9	3	50.5	3	32.6	30.7	30.8	30.6	30.7	0	31.2	3
Mn	124	129	120	125	5	124	4	286	292	285	319	298	6	295	5	264	279	222	218	239	14	246	12
Fe	17300	16400	16500	16500	1	16800	3	51700	53400	49200	51900	51500	4	51600	3	40100	38200	37500	38500	38100	1	38600	3
Co	1.98	2.50	2.26	2.38	7	2.25	11	8.12	10.7	8.93	9.36	9.67	10	9.28	12	3.31	4.04	2.84	2.63	3.17	24	3.21	19
Cu	9.72	11.3	11.5	11.4	1	10.8	9	14.3	16.4	15.5	15.9	16.0	3	15.5	6	12.1	13.2	11.8	12.0	12.3	6	12.3	5
Zn	16.7	19.8	16.8	18.3	11	17.8	10	83.3	80.5	85.2	92.4	86.0	7	85.3	6	63.2	58.2	43.0	45.8	49.0	17	52.5	18
Rb	112	79.2	103	91.0	18	98.0	17	50.0	13.6	24.7	35.9	24.7	45	31.0	50	79.9	53.3	65.0	72.7	63.7	15	67.7	17
Sr	6.56	2.63	8.77	5.70	76	5.99	52	30.6	7.42	13.1	22.8	14.4	54	18.5	56	41.5	16.4	27.8	25.5	23.2	26	27.8	37
Y	3.45	1.55	2.21	1.88	25	2.40	40	5.40	1.50	2.33	6.70	3.51	80	3.98	62	4.80	1.87	2.51	2.25	2.21	15	2.86	46
Zr	268	259	266	262	2	264	2	343	341	312	310	321	5	327	5	471	413	471	456	447	7	453	6
Nb	43.4	43.3	42.0	42.6	2	42.9	2	27.2	31.2	29.0	29.7	30.0	4	29.3	6	26.9	26.6	23.7	23.0	24.4	8	25.0	8
Mo	5.21	4.42	4.00	4.21	7	4.54	14	4.15	4.47	3.26	3.35	3.69	18	3.81	16	4.47	8.27	5.87	4.91	6.35	27	5.88	29
Cd	9.28E-02	3.02E-02	1.67E-02	2.34E-02	41	4.65E-02	87	0.140	0.179	0.179	8.37E-02	0.147	37	0.15	31	0.290	0.090	0.266	0.118	0.158	60	0.191	53
Sn	14.4	15.4	14.0	14.7	7	14.6	5	10.1	11.6	30.2	10.8	17.5	63	15.67	62	9.30	8.80	8.68	7.34	8.27	10	8.53	10
Sb	4.53E-02	0.184	0.103	0.144	40	0.111	63	4.00E-02	0.191	0.157	0.169	0.173	10	0.139	49	0.311	0.259	0.298	0.326	0.294	11	0.298	10
Cs	15.0	1.35	1.62	1.49	13	6.01	130	4.06	0.919	1.08	1.33	1.11	18	1.85	81	6.16	0.743	2.00	2.41	1.72	51	2.83	82
Ba	144	17.8	71.4	44.6	85	77.8	82	119	35.0	64.2	88.8	62.7	43	76.6	46	231	90.6	198	219	169	41	185	35
La	10.7	5.89	10.8	8.35	42	9.14	31	9.62	2.39	4.40	14.0	6.93	89	7.60	69	10.3	8.30	8.24	8.86	8.47	4	8.93	11
Ce	25.5	16.0	27.1	21.6	37	22.9	26	32.3	8.53	15.1	44.4	22.7	84	25.1	65	15.5	12.3	12.2	12.9	12.4	3	13.2	12
Pr	2.68	1.85	2.99	2.42	33	2.51	24	2.19	0.651	1.16	3.48	1.76	85	1.87	67	2.38	1.79	1.75	1.87	1.81	3	1.95	15
Nd	10.0	6.86	10.4	8.61	29	9.08	21	8.52	2.50	4.53	12.3	6.44	80	6.96	62	8.66	5.62	5.84	6.01	5.82	3	6.53	22
Sm	2.12	1.15	1.87	1.51	34	1.71	30	1.81	0.538	0.948	2.43	1.31	76	1.43	60	1.87	1.01	1.19	0.982	1.06	11	1.27	33
Eu	0.164	1.27E-02	1.04E-02	1.16E-02	14	6.22E-02	141	0.210	5.61E-02	7.30E-02	0.315	0.148	98	0.163	75	0.308	0.108	0.102	6.74E-02	9.26E-02	24	0.147	75
Gd	1.33	0.679	1.00	0.839	27	1.00	33	1.35	0.408	0.668	1.73	0.935	75	1.04	59	1.23	0.512	0.648	0.624	0.595	12	0.753	43
Tb	0.308	0.098	0.116	0.107	12	0.174	67	0.250	8.41E-02	0.147	0.356	0.196	73	0.209	57	0.301	0.123	0.114	9.86E-02	0.112	11	0.159	60
Dy	1.09	0.517	0.668	0.592	18	0.758	39	1.66	0.579	0.840	2.32	1.25	75	1.35	59	1.50	0.537	0.811	0.620	0.656	21	0.868	51
Ho	0.252	8.17E-02	0.114	0.098	23	0.149	61	0.300	0.108	0.155	0.422	0.229	74	0.247	58	0.349	0.138	0.148	0.123	0.136	9	0.190	56
Er	0.643	0.253	0.412	0.333	34	0.436	45	0.980	0.335	0.525	1.26	0.707	69	0.775	54	0.934	0.436	0.463	0.407	0.436	6	0.560	45
Tm	0.138	4.66E-02	4.96E-02	4.81E-02	4	7.81E-02	67	0.150	4.74E-02	6.40E-02	0.205	0.105	82	0.117	64	0.247	7.70E-02	6.72E-02	5.74E-02	6.72E-02	15	0.112	80
Yb	0.648	0.324	0.410	0.367	17	0.461	36	1.11	0.446	0.601	1.53	0.857	68	0.920	54	1.19	0.609	0.743	0.588	0.647	13	0.783	36
Lu	0.154	3.88E-02	9.03E-02	6.45E-02	56	9.42E-02	61	0.140	6.29E-02	8.58E-02	0.219	0.123	69	0.127	55	0.230	0.106	9.22E-02	9.14E-02	9.66E-02	9	0.130	52
Hf	8.75	8.62	9.01	8.82	3	8.79	2	10.3	10.7	10.0	9.76	10.2	5	10.2	4	13.5	12.7	14.3	13.6	13.5	6	13.5	5
Tl	1.57	0.915	0.901	0.908	1	1.13	34	1.40	0.787	0.691	0.693	0.723	8	0.893	38	1.03	0.870	0.732	0.710	0.771	11	0.835	18
Pb	38.5	19.9	34.5	27.2	38	31.0	32	36.9	33.6	34.4	37.8	35.3	6	35.7	6	34.9	29.5	36.5	36.5	34.2	12	34.4	10
Bi	1.48	1.92	1.88	1.90	1	1.76	14	0.610	1.15	1.05	1.04	1.08	6	0.962	25	0.553	1.30	1.06	0.883	1.08	19	0.949	33
Th	16.4	27.9	31.7	29.8	9	25.3	31	22.3	16.7	16.2	33.7	22.2	45	22.2	37	9.04	14.5	13.4	14.5	14.2	5	12.9	20
U	8.82	14.3	14.3	14.3	0	12.4	25	21.9	23.4	22.4	22.9	22.9	2	22.7	3	13.2	14.2	15.3	15.4	15.0	4	14.5	7

Appendix 7b: Soil type 2 soil replicates measured elemental concentration data (mg/kg) (continued).

Geo code (500k)	Dgrr							
Geo code (25k)	Dgne							
Batch	1	4	4	4	Batch 4		Overall	
Tube ID	38	13	14	15				
Sample ID	2.11 sub	2.11 sub	2.11 sub	2.11 sub	Average	RSD (%)	Average	RSD (%)
Al	73500	35600	43900	36300	38600	12	47300	38
Sc	9.34	5.58	7.52	5.86	6.32	17	7.08	25
Ti	9710	7610	8140	8090	7950	4	8390	11
V	132	116	121	121	119	2	123	5
Cr	59.2	52.2	51.8	53.5	52.5	2	54.2	6
Mn	877	738	774	765	759	2	788	8
Fe	73200	66400	67100	66700	66700	1	68300	5
Co	15.8	13.2	14.5	14.2	14.0	5	14.4	8
Cu	25.2	21.4	23.0	21.4	22.0	4	22.8	8
Zn	113	93.4	92.0	92.4	92.6	1	97.6	10
Rb	45.8	21.7	35.3	32.1	29.7	24	33.7	29
Sr	60.0	32.5	42.6	32.5	35.9	16	41.9	31
Y	3.38	1.53	2.04	1.55	1.71	17	2.13	41
Zr	289	235	241	255	244	4	255	9
Nb	29.8	25.6	28.0	26.7	26.8	4	27.5	6
Mo	0.352	0.521	7.36E-02	-0.32	9.15E-02	460	0.16	234
Cd	0.303	0.159	0.220	0.171	0.184	17	0.213	30
Sn	4.12	3.94	3.63	3.82	3.79	4	3.88	5
Sb	0.102	0.101	0.221	0.182	0.168	36	0.151	39
Cs	3.38	1.28	1.54	1.05	1.29	19	1.81	59
Ba	298	240	293	223	252	14	263	14
La	4.73	2.11	3.43	2.62	2.72	24	3.22	35
Ce	19.3	9.38	14.5	10.7	11.5	23	13.5	33
Pr	1.15	0.623	0.853	0.632	0.703	19	0.815	30
Nd	4.38	2.37	3.33	2.39	2.70	20	3.12	31
Sm	1.29	0.684	0.678	0.620	0.660	5	0.819	39
Eu	0.419	6.27E-02	0.124	5.29E-02	8.00E-02	48	0.165	105
Gd	1.05	0.422	0.512	0.365	0.433	17	0.587	53
Tb	0.414	8.02E-02	9.96E-02	7.96E-02	8.65E-02	13	0.168	97
Dy	1.280	0.551	0.783	0.514	0.616	24	0.782	45
Ho	0.448	0.109	0.124	9.54E-02	0.110	13	0.194	87
Er	0.908	0.330	0.453	0.331	0.372	19	0.506	54
Tm	0.329	6.37E-02	5.31E-02	4.01E-02	5.23E-02	23	0.122	114
Yb	0.915	0.431	0.486	0.345	0.421	17	0.544	47
Lu	0.354	5.22E-02	5.78E-02	5.57E-02	5.53E-02	5	0.130	115
Hf	8.06	7.02	7.27	7.36	7.22	2	7.43	6
Tl	0.761	0.540	0.557	0.463	0.520	10	0.580	22
Pb	27.3	26.5	27.5	26.2	26.8	3	26.9	2
Bi	0.208	0.293	0.324	0.274	0.297	8	0.275	18
Th	7.49	5.78	7.64	6.27	6.56	15	6.80	13
U	4.96	4.87	5.13	5.24	5.08	4	5.05	3

Appendix 7c: Soil type 3 soil replicates measured elemental concentration data (mg/kg) (continued overleaf).

Geo code (500k)	ODsm																			
Geo code (25k)	ODq												ODqp							
Batch	2	2	2	Batch 2		4	4	4	Batch 4		Overall		2	4	4	4	Batch 4		Overall	
Tube ID	28	29	30			40	41	42					36	46	47	48				
Sample ID	3.12 top	3.12 top	3.12 top	Average	RSD (%)	3.12 top	3.12 top	3.12 top	Average	RSD (%)	Average	RSD (%)	3.15 top	3.15 top	3.15 top	3.15 top	Average	RSD (%)	Average	RSD (%)
Al	5340	6430	6240	6000	10	3908	5430	5210	4850	17	5430	17	12700	15900	13700	13600	14400	9	14000	10
Sc	1.87	2.14	2.35	2.12	11	1.90	2.13	1.99	2.01	6	2.06	9	3.21	4.60	3.87	3.80	4.09	11	3.87	15
Ti	2710	2790	2560	2690	4	2760	2620	2720	2710	3	2700	3	4120	3700	3950	3070	3570	13	3710	12
V	12.3	13.8	13.0	13.0	5	12.7	11.6	12.8	12.4	5	12.7	6	37.3	36.1	35.7	34.3	35.4	3	35.9	3
Cr	9.27	10.13	8.58	9.33	8	12.12	9.76	9.75	10.5	13	9.94	12	38.9	37.7	34.8	36.6	36.4	4	37.0	5
Mn	48.3	52.0	49.6	49.9	4	49.1	51.0	51.9	50.6	3	50.3	3	47.3	50.7	48.8	48.0	49.2	3	48.7	3
Fe	1510	1580	1480	1520	3	1590	1570	1620	1590	2	1560	3	9770	10200	10100	10000	10100	1	10000	2
Co	0.413	0.415	0.412	0.413	0	0.543	0.339	0.590	0.491	27	0.452	21	0.908	1.16	1.18	0.649	0.998	30	0.976	26
Cu	6.41	7.20	6.07	6.56	9	7.41	6.72	6.69	6.94	6	6.75	7	7.02	7.66	8.12	7.60	7.79	4	7.60	6
Zn	4.97	4.49	4.12	4.53	9	8.07	6.20	4.71	6.33	27	5.43	27	12.8	11.0	13.8	11.2	12.0	13	12.2	11
Rb	15.0	15.8	14.8	15.2	3	15.7	15.9	14.7	15.5	4	15.3	3	20.2	28.2	28.7	26.9	27.9	3	26.0	15
Sr	19.1	23.8	21.9	21.6	11	18.5	24.1	23.1	21.9	14	21.8	11	11.4	15.6	14.8	13.0	14.5	9	13.7	14
Y	7.86	8.74	7.99	8.19	6	8.17	10.2	8.63	9.01	12	8.6	10	8.9	11.8	10.3	10.1	10.8	9	10.3	11
Zr	161	168	143	157	8	182	167	172	174	5	165	8	209	215	218	219	218	1	216	2
Nb	4.73	4.60	4.60	4.64	2	6.23	5.56	6.38	6.06	7	5.35	15	9.45	8.82	10.4	8.05	9.09	13	9.18	11
Mo	0.153	9.78E-02	-4.24E-02	6.95E-02	145	-0.904	-1.065	-0.940	-0.970	-9	-0.450	-128	0.140	-1.44	-1.41	-1.66	-1.50	-9	-1.09	-76
Cd	7.90E-02	3.16E-02	0.112	7.43E-02	55	2.11E-02	2.13E-03	6.99E-02	3.10E-02	113	5.27E-02	79	0.221	4.19E-02	0.175	0.118	0.112	60	0.139	56
Sn	0.740	0.610	0.603	0.651	12	0.834	0.714	0.720	0.756	9	0.704	12	2.06	1.92	1.90	1.94	1.92	1	1.95	4
Sb	8.54E-02	0.190	0.127	0.134	39	0.125	0.249	0.145	0.173	39	0.154	38	1.34	1.15	1.23	1.03	1.14	9	1.19	11
Cs	1.93	2.09	2.05	2.02	4	1.52	1.98	1.91	1.81	14	1.92	11	1.50	2.08	2.22	1.86	2.05	9	1.91	16
Ba	80.9	87.6	82.3	83.6	4	79.2	82.4	83.7	81.8	3	82.7	3	141	194	199	177	190	6	178	15
La	16.2	17.0	16.1	16.4	3	15.7	19.2	17.6	17.5	10	17.0	8	15.0	23.5	20.6	20.6	21.6	8	19.9	18
Ce	29.5	32.1	30.6	30.7	4	29.5	37.8	33.8	33.7	12	32.2	10	34.3	50.6	45.2	44.6	46.8	7	43.7	16
Pr	3.77	3.87	3.78	3.81	2	3.63	4.51	4.02	4.06	11	3.93	8	4.15	5.98	5.33	5.29	5.53	7	5.19	15
Nd	13.5	14.0	13.5	13.7	2	13.2	16.4	14.6	14.7	11	14.2	8	16.0	22.0	20.0	19.3	20.5	7	19.34	13
Sm	2.50	2.42	2.56	2.49	3	2.48	3.22	2.69	2.80	13	2.65	11	2.97	3.87	3.48	3.53	3.63	6	3.46	11
Eu	0.334	0.349	0.360	0.348	4	0.270	0.421	0.378	0.356	22	0.352	14	0.424	0.565	0.596	0.448	0.536	15	0.508	17
Gd	1.65	1.82	1.71	1.73	5	1.74	2.03	1.97	1.91	8	1.82	8	2.06	2.78	2.36	2.54	2.56	8	2.43	12
Tb	0.280	0.305	0.308	0.298	5	0.296	0.357	0.314	0.322	10	0.310	8	0.393	0.480	0.441	0.387	0.436	11	0.425	10
Dy	1.57	1.67	1.49	1.58	6	1.67	1.92	1.70	1.77	8	1.67	9	2.23	2.81	2.42	2.28	2.50	11	2.43	11
Ho	0.307	0.313	0.305	0.308	1	0.311	0.390	0.321	0.341	13	0.324	10	0.451	0.516	0.436	0.456	0.469	9	0.465	8
Er	0.863	0.908	0.767	0.846	8	0.849	1.162	0.912	0.974	17	0.910	15	1.43	1.41	1.33	1.41	1.38	3	1.39	3
Tm	0.131	0.142	0.118	0.130	9	0.134	0.185	0.135	0.151	19	0.141	16	0.204	0.215	0.179	0.185	0.193	10	0.196	9
Yb	0.895	1.055	0.956	0.969	8	0.930	1.24	1.13	1.10	14	1.03	13	1.62	1.62	1.39	1.47	1.49	8	1.52	8
Lu	0.131	0.172	0.130	0.144	16	0.148	0.189	0.157	0.165	13	0.155	15	0.213	0.230	0.189	0.201	0.207	10	0.208	8
Hf	4.75	4.66	4.20	4.54	6	5.54	5.16	5.44	5.38	4	4.96	10	6.29	6.26	6.22	6.29	6.26	1	6.27	1
Tl	7.86E-02	7.85E-02	7.64E-02	7.78E-02	2	7.13E-02	4.87E-02	7.27E-02	6.42E-02	21	7.10E-02	16	0.417	0.199	0.222	0.194	0.205	7	0.258	41
Pb	4.68	4.96	5.15	4.93	5	4.84	7.07	4.66	5.52	24	5.23	18	10.3	10.7	10.8	10.5	10.6	1	10.6	2
Bi	0.110	0.101	9.06E-02	0.100	10	9.10E-02	6.59E-02	6.55E-02	7.41E-02	20	8.73E-02	21	5.07E-02	6.82E-02	5.05E-02	4.56E-02	5.48E-02	22	5.37E-02	18
Th	5.79	6.01	5.97	5.92	2	6.34	8.17	7.18	7.23	13	6.58	14	9.14	11.5	10.5	10.1	10.7	7	10.3	10
U	1.99	2.03	1.91	1.98	3	2.18	2.08	1.97	2.08	5	2.03	5	3.41	3.39	3.39	3.28	3.35	2	3.37	2

Appendix 7c: Soil type 3 soil replicates measured elemental concentration data (mg/kg) (continued).

Geo code (500k)	ODsm								Psp									
Geo code (25k)	ODqm								Pfs									
Batch	2	4	4	4	Batch 4		Overall		4	4	4	Batch 4		4	4	4	Batch 4	
Tube ID	49	43	44	45					34	35	36			37	38	39		
Sample ID	3.22 sub	3.22 sub	3.22 sub	3.22 sub	Average	RSD (%)	Average	RSD (%)	3.9 sub	3.9 sub	3.9 sub	Average	RSD (%)	3.9 top	3.9 top	3.9 top	Average	RSD (%)
Al	15000	18100	16000	18800	17600	8	17000	11	22700	23000	30500	25400	17	7550	7100	6720	7120	6
Sc	3.54	4.47	4.32	4.88	4.56	6	4.30	13	4.54	4.54	5.83	4.97	15	1.54	1.42	1.21	1.39	12
Ti	3100	4000	3500	4120	3880	9	3680	13	6960	7520	5370	6620	17	1190	1340	4210	2250	76
V	39.35	41.44	40.57	43.01	41.7	3	41.1	4	94.8	99.1	86.5	93.5	7	22.2	20.4	27.5	23.4	16
Cr	42.5	39.7	43.1	41.2	41.3	4	41.6	4	57.8	59.6	57.7	58.3	2	20.8	21.6	20.9	21.1	2
Mn	1130	1180	1230	1200	1200	2	1190	4	68.5	74.3	69.2	70.7	4	93.3	90.8	89.5	91.2	2
Fe	8460	8790	9090	8980	8950	2	8830	3	27000	26700	26400	26700	1	6270	6370	6040	6230	3
Co	2.39	2.11	1.97	2.15	2.07	5	2.15	8	4.36	4.24	4.09	4.23	3	1.21	1.39	1.42	1.34	8
Cu	5.63	69.5	6.31	6.38	27.4	133	22.0	144	6.28	5.94	6.96	6.39	8	6.44	5.78	5.74	5.99	7
Zn	16.3	52.0	15.3	15.2	27.5	77	24.7	74	13.6	14.0	12.4	13.3	6	5.27	9.81	6.28	7.12	34
Rb	38.0	53.3	44.0	51.5	49.6	10	46.7	15	14.5	9.14	14.0	12.6	24	22.3	20.1	21.3	21.2	5
Sr	17.8	24.4	19.7	23.7	22.6	11	21.4	15	11.9	3.66	14.1	9.89	56	19.9	15.6	15.8	17.1	14
Y	9.4	11.1	10.4	15.1	12.2	21	11.5	22	6.05	4.40	8.56	6.34	33	4.44	3.94	3.19	3.86	16
Zr	312	301	311	312	308	2	309	2	272	285	267	275	4	165	144	179	163	11
Nb	5.52	8.67	6.32	8.61	7.87	17	7.28	22	14.4	18.5	18.6	17.2	14	1.50	1.87	6.81	3.39	87
Mo	-7.55E-02	-0.791	-1.38	-1.38	-1.18	-29	-0.906	-68	-0.275	-0.259	3.55	1.18	219	1.07	-8.82E-02	3.96E-02	0.340	186
Cd	9.60E-02	2.25E-02	4.19E-02	2.12E-02	2.85E-02	41	4.54E-02	77	6.46E-02	0.150	7.25E-02	9.55E-02	49	4.62E-02	2.63E-02	8.55E-02	5.27E-02	57
Sn	1.83	3.62	2.23	2.30	2.72	29	2.50	31	3.57	3.84	2.79	3.40	16	0.631	0.897	1.41	0.981	41
Sb	0.303	0.573	0.337	0.436	0.449	26	0.41	29	0.522	0.640	0.471	0.544	16	4.45E-02	8.72E-02	0.356	0.163	104
Cs	2.46	3.55	2.10	1.94	2.53	35	2.51	29	0.666	0.271	0.800	0.579	48	1.64	1.09	1.05	1.26	26
Ba	153	213	128	141	160	28	159	24	66.3	15.0	53.6	45.0	59	130	114	104	116	11
La	20.0	26.7	24.2	35.3	28.7	20	26.5	24	12.3	8.71	13.1	11.4	20	14.7	14.0	14.6	14.4	3
Ce	43.4	56.7	51.9	74.8	61.1	20	56.7	23	28.0	20.6	30.9	26.5	20	29.3	27.8	28.8	28.6	3
Pr	5.24	6.67	6.07	8.77	7.17	20	6.69	23	3.21	2.50	3.71	3.14	19	3.31	3.25	3.39	3.31	2
Nd	19.8	25.0	22.6	32.4	26.7	19	24.97	22	11.9	9.57	13.8	11.7	18	11.9	11.4	12.3	11.9	4
Sm	3.43	4.45	4.02	5.61	4.69	18	4.38	21	2.23	1.86	2.81	2.30	21	2.06	1.97	1.95	1.99	3
Eu	0.500	0.636	0.612	0.757	0.668	12	0.626	17	0.248	0.170	0.282	0.233	25	0.163	0.123	0.100	0.129	25
Gd	2.41	2.93	2.57	3.70	3.07	19	2.90	20	1.42	1.21	1.77	1.47	19	1.42	1.14	1.26	1.27	11
Tb	0.391	0.425	0.414	0.595	0.478	21	0.456	21	0.263	0.186	0.335	0.261	29	0.205	0.166	0.148	0.173	17
Dy	2.08	2.42	2.32	3.34	2.69	21	2.54	22	1.46	1.10	2.19	1.58	35	1.06	0.881	0.763	0.901	17
Ho	0.422	0.476	0.449	0.623	0.516	18	0.492	18	0.286	0.207	0.425	0.306	36	0.177	0.159	0.128	0.155	16
Er	1.25	1.47	1.22	1.81	1.50	20	1.44	19	0.865	0.696	1.33	0.962	34	0.537	0.479	0.324	0.447	25
Tm	0.188	0.192	0.193	0.265	0.217	19	0.210	18	0.139	0.096	0.176	0.137	29	5.57E-02	5.22E-02	4.45E-02	5.08E-02	11
Yb	1.30	1.55	1.46	2.16	1.72	22	1.62	23	1.17	0.885	1.45	1.17	24	0.474	0.439	0.325	0.413	19
Lu	0.195	0.233	0.234	0.331	0.266	21	0.248	23	0.151	0.113	0.236	0.167	38	6.45E-02	6.14E-02	4.53E-02	5.70E-02	18
Hf	8.70	8.62	8.91	8.81	8.78	2	8.76	1	7.89	7.90	7.71	7.83	1	5.07	4.44	5.59	5.03	11
Tl	0.499	0.257	0.217	0.218	0.231	10	0.298	45	0.131	9.31E-02	0.422	0.215	84	0.243	0.159	0.099	0.167	43
Pb	29.7	34.0	28.6	29.6	30.8	9	30.5	8	13.3	8.22	13.0	11.5	25	10.0	9.51	9.27	9.61	4
Bi	5.98E-02	0.106	7.93E-02	5.91E-02	8.14E-02	29	7.60E-02	29	0.123	0.105	0.626	0.285	104	0.249	0.175	8.70E-02	0.170	48
Th	9.25	10.7	9.55	13.9	11.4	20	10.9	20	11.2	12.3	12.3	12.0	5	7.72	8.08	8.44	8.08	4
U	4.67	4.51	4.50	4.65	4.56	2	4.58	2	3.62	3.73	3.69	3.68	2	2.22	2.18	2.27	2.22	2

Appendix 7d: Soil type 4 soil replicates measured elemental concentration data (mg/kg) (continued overleaf).

Geo code (500k)	Qa																				
Geo code (25k)	Qha																				
Batch	3	4	4	4	Batch 4		Overall		3	3	3	Batch 3		3	4	4	4	Batch 4		Overall	
Tube ID	16	25	26	27					24	25	26			29	28	29	30				
Sample ID	4.4 sub	4.4 sub	4.4 sub	4.4 sub	Average	RSD (%)	Average	RSD (%)	4.8 sub	4.8 sub	4.8 sub	Average	RSD (%)	4.9 top	4.9 top	4.9 top	4.9 top	Average	RSD (%)	Average	RSD (%)
Al	39800	23600	23200	26060	24300	6	28200	28	7620	6460	7280	7120	8	8260	5970	5960	4300	5406	18	6120	27
Sc	6.15	3.78	4.52	4.59	4.30	10	4.76	21	3.15	2.61	2.89	2.88	9	2.18	1.51	2.02	2.05	1.86	16	1.94	15
Ti	3940	3860	3780	3760	3800	1	3840	2	1090	596	951	878	29	2110	4740	5050	4300	4700	8	4050	33
V	57.7	55.2	54.5	57.1	55.6	2	56.1	3	11.6	8.6	11.1	10.4	15	18.2	23.4	25.5	23.0	24.0	5	22.5	14
Cr	48.2	49.6	47.3	50.1	49.0	3	48.8	3	17.1	17.1	16.4	16.9	2	16.5	17.7	18.1	17.2	17.7	3	17.4	4
Mn	670	699	646	533	626	13	637	11	49.4	46.8	45.2	47.1	5	149	140	149	156	148	5	148	4
Fe	24400	25100	26000	26000	25700	2	25300	3	3110	3030	2970	3040	2	4010	4150	4290	4160	4200	2	4150	3
Co	11.5	11.0	10.7	10.4	10.7	3	10.9	4	0.642	0.620	0.650	0.638	2	1.21	1.27	1.30	1.60	1.39	13	1.34	13
Cu	12.4	15.3	14.5	12.7	14.2	9	13.7	10	4.66	4.52	3.75	4.31	11	8.03	7.43	8.38	8.58	8.13	8	8.10	6
Zn	61.9	58.0	63.2	49.6	56.9	12	58.2	11	6.98	3.17	5.75	5.30	37	12.4	11.1	8.5	12.4	10.7	19	11.1	17
Rb	79.9	53.4	59.9	78.7	64.0	21	67.9	20	26.5	17.2	24.4	22.7	22	21.7	21.1	19.2	19.4	19.9	5	20.3	6
Sr	36.1	20.4	22.6	29.9	24.3	20	27.2	26	17.1	11.3	16.2	14.9	21	18.3	16.3	16.8	12.8	15.3	15	16.1	15
Y	14.4	7.75	6.98	9.41	8.05	15	9.63	35	15.7	10.6	14.0	13.4	19	6.31	5.22	6.03	5.66	5.63	7	5.80	8
Zr	343	366	370	397	378	4	369	6	260	257	251	256	2	137	150	156	150	152	2	148	5
Nb	18.4	19.1	18.7	18.8	18.9	1	18.8	2	0.645	0.293	1.06	0.667	58	2.17	5.60	7.85	5.36	6.27	22	5.24	45
Mo	1.12	0.853	0.655	0.300	0.602	47	0.732	47	0.809	0.317	0.183	0.436	75	-0.097	-0.427	-0.614	-0.862	-0.634	-34	-0.500	-65
Cd	0.268	0.401	0.314	0.352	0.356	12	0.334	17	0.131	7.54E-02	7.35E-02	9.32E-02	35	8.70E-02	0.160	0.126	7.33E-02	0.120	36	0.111	35
Sn	7.02	6.46	6.94	6.87	6.76	4	6.82	4	0.410	0.293	0.545	0.416	30	0.691	0.978	1.21	1.06	1.08	11	0.984	22
Sb	0.144	0.104	0.165	0.145	0.138	23	0.140	18	2.94E-02	1.97E-02	8.45E-02	4.45E-02	79	0.103	0.173	0.271	0.177	0.207	27	0.181	38
Cs	8.40	2.07	2.63	5.31	3.34	52	4.60	63	2.07	1.85	1.89	1.94	6	1.85	1.79	1.60	1.20	1.53	20	1.61	18
Ba	331	233	245	314	264	17	281	18	96.3	85.3	90.8	90.8	6	112	108	107	101	105	3	107	4
La	30.0	22.0	20.6	25.6	22.7	11	24.5	17	20.2	25.3	21.8	22.4	12	18.1	15.2	14.0	15.6	14.9	6	15.7	11
Ce	57.1	44.3	40.5	51.3	45.4	12	48.3	15	38.3	50.0	43.0	43.8	13	37.7	32.5	29.6	29.8	30.6	5	32.4	12
Pr	7.60	5.75	5.35	6.64	5.91	11	6.33	16	4.70	5.87	4.99	5.19	12	4.08	3.62	3.26	3.56	3.48	6	3.63	9
Nd	28.7	20.6	19.2	24.2	21.3	12	23.2	18	17.2	21.0	18.4	18.9	10	15.1	13.0	12.0	13.0	12.7	4	13.3	10
Sm	5.30	3.91	3.49	4.48	3.96	13	4.29	18	3.05	3.83	3.35	3.41	12	2.74	2.34	2.07	2.05	2.15	7	2.30	14
Eu	0.511	0.286	0.241	0.331	0.286	16	0.342	35	0.321	0.439	0.396	0.385	15	0.250	0.233	0.206	0.176	0.205	14	0.216	15
Gd	3.70	2.57	2.28	2.79	2.55	10	2.84	22	2.09	2.64	2.33	2.35	12	1.73	1.53	1.31	1.46	1.43	8	1.51	11
Tb	0.622	0.391	0.368	0.431	0.397	8	0.453	25	0.348	0.449	0.416	0.404	13	0.238	0.226	0.213	0.208	0.216	4	0.221	6
Dy	3.55	1.92	1.90	2.46	2.09	15	2.46	32	1.97	2.65	2.49	2.37	15	1.38	1.25	1.28	1.03	1.19	11	1.23	12
Ho	0.700	0.375	0.342	0.438	0.385	13	0.464	35	0.394	0.525	0.518	0.479	15	0.257	0.211	0.240	0.194	0.215	11	0.225	13
Er	2.10	1.00	0.963	1.29	1.09	16	1.34	39	1.19	1.61	1.46	1.42	15	0.685	0.534	0.703	0.565	0.601	15	0.622	14
Tm	0.308	0.146	0.123	0.200	0.157	25	0.194	42	0.181	0.266	0.249	0.232	19	0.109	8.18E-02	0.107	7.51E-02	8.80E-02	19	9.32E-02	19
Yb	2.33	1.23	1.12	1.54	1.30	17	1.56	35	1.30	1.85	1.70	1.62	18	0.82	0.69	0.77	0.65	0.70	8	0.73	11
Lu	0.351	0.181	0.181	0.248	0.203	19	0.240	33	0.219	0.310	0.284	0.271	17	0.111	0.097	0.111	0.102	0.103	7	0.105	7
Hf	10.9	11.1	11.1	11.6	11.3	3	11.2	3	8.34	7.79	7.65	7.93	5	3.95	4.14	4.17	4.13	4.15	1	4.10	2
Tl	1.10	0.686	0.676	0.620	0.661	5	0.771	29	0.132	0.146	0.131	0.136	6	0.164	0.114	8.86E-02	0.109	0.104	13	0.119	27
Pb	28.5	28.0	27.3	26.8	27.4	2	27.7	3	4.94	4.58	4.81	4.78	4	6.92	7.04	6.62	6.92	6.86	3	6.87	3
Bi	0.566	0.776	0.771	0.722	0.756	4	0.709	14	0.254	0.151	0.101	0.169	46	4.02E-02	8.04E-02	2.83E-02	3.43E-02	4.77E-02	60	4.58E-02	51
Th	24.6	22.6	20.1	22.9	21.9	7	22.5	8	11.9	8.83	10.5	10.4	15	7.58	6.74	5.82	6.31	6.29	7	6.61	11
U	15.2	15.1	14.8	15.1	15.0	1	15.0	1	3.46	3.04	3.15	3.22	7	2.14	2.05	1.89	2.00	1.98	4	2.02	5

Appendix 7d: Soil type 4 soil replicates measured elemental concentration data (mg/kg) (continued).

Geo code (500k)	Qa							
Geo code (25k)	Qpao							
Batch	3	4	4	4	Batch 4		Overall	
Tube ID	35	31	32	33				
Sample ID	4.13 top	4.13 top	4.13 top	4.13 top	Average	RSD (%)	Average	RSD (%)
Al	32800	23900	29900	23300	25700	14	27500	17
Sc	2.45	2.89	2.80	2.74	2.81	3	2.72	7
Ti	3850	3650	3730	3730	3700	1	3740	2
V	53.4	50.9	51.2	51.6	51.2	1	51.8	2
Cr	28.7	30.6	29.5	32.8	31.0	5	30.4	6
Mn	415	397	394	412	401	2	404	3
Fe	24500	25800	25700	26600	26000	2	25600	3
Co	6.07	4.12	3.53	3.45	3.70	10	4.29	28
Cu	12.2	9.89	8.69	10.9	9.84	11	10.4	14
Zn	36.9	35.8	32.9	35.2	34.6	4	35.2	5
Rb	117	104	87.3	62.3	84.5	25	92.7	26
Sr	34.5	33.2	35.1	20.9	29.7	26	30.9	22
Y	4.33	3.55	4.49	1.79	3.27	42	3.54	35
Zr	368	349	378	372	366	4	367	3
Nb	23	22	24	23	23	4	23	3
Mo	1.79	0.840	0.706	0.772	0.773	9	1.03	50
Cd	0.125	0.211	0.096	0.220	0.176	39	0.163	38
Sn	7.16	7.11	7.38	7.23	7.24	2	7.22	2
Sb	0.179	6.55E-02	0.146	0.169	0.127	43	0.140	37
Cs	5.63	4.77	4.02	1.15	3.31	58	3.89	50
Ba	292	279	260	158	232	28	247	25
La	13.9	12.1	10.1	7.66	9.95	22	10.9	25
Ce	34.2	29.7	25.9	19.7	25.1	20	27.4	22
Pr	3.22	2.90	2.70	2.07	2.56	17	2.73	18
Nd	11.5	10.2	9.64	7.28	9.04	17	9.65	18
Sm	1.81	1.82	1.82	1.41	1.68	14	1.72	12
Eu	0.109	8.78E-02	8.44E-02	3.90E-02	7.04E-02	39	8.00E-02	37
Gd	1.29	0.956	1.20	0.689	0.950	27	1.04	26
Tb	0.185	0.174	0.172	0.104	0.150	27	0.159	23
Dy	1.13	0.958	1.17	0.511	0.881	38	0.943	32
Ho	0.212	0.147	0.227	0.110	0.161	37	0.174	32
Er	0.662	0.492	0.679	0.308	0.493	38	0.535	32
Tm	9.91E-02	7.09E-02	0.105	3.34E-02	6.99E-02	52	7.72E-02	43
Yb	0.907	0.767	1.045	0.504	0.772	35	0.806	29
Lu	0.141	0.105	0.176	3.99E-02	0.107	64	0.115	50
Hf	12.1	10.6	12.0	11.6	11.4	6	11.5	6
Tl	1.00	0.485	0.479	0.507	0.490	3	0.617	41
Pb	31.3	30.6	29.1	28.0	29.2	5	29.8	5
Bi	0.702	0.722	0.704	0.745	0.724	3	0.718	3
Th	24.6	19.9	21.3	19.7	20.3	4	21.3	11
U	11.4	10.3	10.6	10.9	10.6	3	10.8	5

Appendix 8a: Soil type 1 samples measured elemental concentration data (mg/kg).

Geo code (500k)	Qrc												Jdtm					
Geo code (25k)	Qptd												Jd					
Batch no. (n)	2	1 (1), 4 (3)	1	1	1	1	2	1	1	1	1 (1), 4 (3)	1	1 (1), 4 (3)	2	2	1	2	2
Tube ID	13	10; 16, 17, 18	14	16	18, 19, 20	22	14	11	15	17	21; 22, 23, 24	23	12; 19, 20, 21	15	17	13	16	18
Sample ID	1.3 sub	1.4 sub (av)	1.9 sub	1.10 sub	1.11 sub (av)	1.14 sub	1.3 top	1.4 top	1.9 top	1.10 top	1.11 top (av)	1.14 top	1.7 sub (av)	1.8 sub	1.13 sub	1.7 top	1.8 top	1.13 top
Al	32500	31400	63700	104000	46300	44900	21600	52200	36800	40500	20800	26000	32300	52700	25700	38100	27100	29400
Sc	10.0	11.5	24.2	36.9	14.6	16.4	8.70	15.5	13.9	14.1	5.04	7.16	9.33	19.3	5.72	13.2	9.90	4.70
Ti	3610	4200	7110	4530	10200	7850	3230	4240	6400	4500	10300	7960	6260	3600	5130	4990	1860	4130
V	156	170	291	259	219	263	131	160	214	201	137	116	227	144	233	180	72.709	116
Cr	158	143	202	323	86.7	29.4	128	138	147	220	50.1	22.7	43.4	25.4	185.8	32.4	15.5	71.2
Mn	2860	697	1630	464	636	371	2260	580	2650	3520	1300	710	1810	6410	854	3520	5680	1990
Fe	44200	47300	77500	93600	59300	67700	36200	43900	56900	67000	38000	27700	75300	50900	68800	55700	22200	29000
Co	37.0	23.3	60.3	63.5	62.9	53.7	32.8	20.0	58.4	46.6	51.2	27.4	40.0	38.7	29.4	36.8	15.9	19.2
Cu	39.2	28.9	61.5	73.4	57.1	63.2	35.1	29.5	34.1	47.0	36.9	34.7	84.9	46.7	52.3	67.4	37.3	23.3
Zn	143	78.2	71.2	76.2	57.5	50.6	113.0	89.0	91.5	84.9	49.1	39.0	75.7	142.6	71.8	84.8	74.3	64.8
Rb	5.04	3.96	14.9	1.86	30.7	15.9	3.22	17.8	4.68	1.97	31.5	39.1	2.16	16.2	0.450	3.88	16.8	39.8
Sr	25.6	34.2	26.8	19.6	29.2	28.0	26.5	59.6	24.7	22.2	25.6	35.6	12.2	77.1	8.4	28.1	83.5	68.5
Y	4.86	3.79	3.96	2.31	3.00	3.02	6.48	8.05	3.70	2.25	1.60	5.73	2.20	10.1	0.864	5.95	6.02	2.45
Zr	126	155	172	98.9	231	170	124	172	152	90.5	253	188	117	67.0	115	94.3	33.1	94.4
Nb	8.14	9.82	9.88	5.12	14.4	11.4	7.34	10.2	8.86	5.66	15.73	13.5	9.32	5.16	8.12	6.89	2.68	6.70
Mo	1.78	0.958	0.416	-0.102	0.111	0.228	1.00	2.55	0.378	-2.32E-03	1.27	0.792	0.185	0.780	0.673	0.496	0.299	0.556
Cd	0.120	0.107	0.133	0.149	0.165	0.145	0.204	0.107	0.143	0.149	8.06E-02	7.28E-02	9.49E-02	0.211	0.184	0.153	0.175	0.194
Sn	2.40	2.97	1.45	1.21	1.77	1.46	1.95	3.17	1.47	1.14	1.60	1.25	1.95	0.945	1.42	1.21	0.363	1.41
Sb	0.253	0.388	5.41E-02	-2.68E-03	0.176	0.155	0.338	0.365	0.129	0.127	0.206	0.156	0.147	7.59E-02	0.185	8.65E-02	0.132	0.258
Cs	2.67	2.60	0.842	0.363	0.601	0.514	2.56	6.16	1.24	0.519	0.703	1.15	0.569	0.705	0.398	1.02	0.551	2.11
Ba	205	134	197	171	280	192	164	197	167	112	340	254	94.0	206	75.5	124	140	387
La	4.28	4.02	4.09	1.07	4.31	3.49	4.75	9.05	6.34	2.00	2.70	11.3	2.75	11.3	0.51	5.65	8.03	4.15
Ce	11.6	10.3	13.2	3.84	10.9	9.80	10.7	22.6	16.4	4.93	6.66	22.8	6.52	20.1	1.20	13.7	11.4	8.80
Pr	1.48	1.55	1.24	0.188	0.884	1.24	1.63	2.84	1.54	0.318	0.669	3.88	0.721	2.43	0.199	1.30	1.40	0.906
Nd	5.96	5.54	5.40	1.54	4.42	4.06	6.41	11.1	6.35	2.30	2.70	10.8	3.10	9.32	0.814	5.90	5.35	3.36
Sm	1.55	1.54	1.29	0.629	0.851	1.02	1.69	2.80	1.35	0.531	0.530	3.60	0.683	2.00	0.174	1.34	1.11	0.574
Eu	0.297	0.511	0.429	0.206	0.161	0.350	0.312	0.779	0.184	0.096	7.69E-02	2.26	0.150	0.685	2.43E-02	0.331	0.312	6.56E-02
Gd	1.39	1.21	1.08	0.584	0.601	0.895	1.70	2.08	0.957	0.430	0.368	2.78	0.542	1.78	0.138	1.12	0.854	0.372
Tb	0.297	0.500	0.324	0.159	8.50E-02	0.275	0.290	0.637	0.168	7.91E-02	5.97E-02	1.98	0.110	0.327	2.62E-02	0.223	0.161	7.21E-02
Dy	1.74	1.52	1.26	0.910	0.801	1.08	1.91	2.55	0.975	0.643	0.431	2.95	0.669	2.15	0.305	1.42	1.02	0.516
Ho	0.350	0.515	0.385	0.233	0.127	0.314	0.394	0.696	0.188	0.121	7.61E-02	1.77	0.134	0.444	3.84E-02	0.315	0.210	0.103
Er	0.949	0.987	0.863	0.662	0.478	0.703	1.03	1.62	0.587	0.404	0.273	2.50	0.418	1.26	0.181	0.814	0.609	0.354
Tm	0.166	0.376	0.265	0.161	0.042	0.225	0.155	0.437	0.102	4.12E-02	1.52E-02	2.29	5.83E-02	0.184	1.72E-02	0.160	8.90E-02	4.85E-02
Yb	0.962	1.08	1.05	0.768	0.590	0.706	0.979	1.69	0.699	0.434	0.291	2.60	0.368	1.05	0.156	0.902	0.595	0.356
Lu	0.141	0.404	0.280	0.172	4.25E-02	0.182	0.139	0.468	0.113	3.83E-02	2.81E-02	1.90	5.99E-02	0.185	1.04E-02	0.145	7.79E-02	3.94E-02
Hf	3.72	4.63	4.82	2.81	6.41	4.64	4.15	5.26	4.19	2.46	7.07	5.06	3.41	1.99	3.12	2.90	1.02	2.50
Tl	0.628	0.268	0.322	0.185	0.483	0.300	0.588	0.507	0.294	0.170	0.524	0.362	0.149	0.225	0.219	0.153	0.108	0.226
Pb	17.3	14.1	10.2	5.69	12.8	14.4	18.9	14.9	13.8	12.2	17.3	13.7	11.7	8.50	9.01	12.0	8.86	12.8
Bi	0.797	0.261	0.118	7.32E-02	5.55E-02	9.45E-02	0.395	0.362	0.161	0.124	0.187	0.668	0.168	0.255	0.148	0.343	0.249	0.116
Th	3.66	4.01	3.62	2.08	4.00	3.41	3.40	7.23	4.86	1.80	2.30	5.22	1.81	3.03	0.741	3.28	1.46	2.34
U	2.05	2.06	1.68	0.942	1.76	1.61	1.87	2.64	1.23	0.748	1.69	1.98	1.52	0.824	1.22	1.18	0.411	1.45

Appendix 8b: Soil type 2 samples measured elemental concentration data (mg/kg) (continued overleaf).

Geo code (500k)	Dgrt								Dgrh					
Geo code (25k)	Dgaap						Dgae		Dgnv				Dgnx	
Batch no. (n)	1	2	1	1 (1), 4 (2)	2	1	2	2	1 (1), 4 (3)	1	1 (1), 4 (3)	1	1	1
Tube ID	24	19	26	25; 4, 6	20	27	21	22	28; 7, 8, 9	30	29; 10, 11, 12	31	32	33
Sample ID	2.1 sub	2.2 sub	2.3 sub	2.1 top (av)	2.2 top	2.3 top	2.4 sub	2.4 top	2.5 sub (av)	2.6 sub	2.5 top (av)	2.6 top	2.7 sub	2.7 top
Al	71400	11300	38600	38700	10200	28000	12000	6690	63200	92800	38900	63600	78100	48300
Sc	4.94	0.878	3.43	2.47	1.30	3.45	1.74	1.03	6.77	9.68	3.89	7.95	9.16	5.72
Ti	3370	3130	6660	3190	2640	5050	5280	2350	6450	7560	5930	5290	6430	4760
V	31.4	56.4	104	28.6	42.6	46.2	57.3	25.3	95.6	112	78.0	81.9	104.8	74.4
Cr	10.7	16.0	29.1	9.6	13.8	18.6	20.6	10.1	50.5	49.7	31.2	39.1	41.4	33.9
Mn	131	122	97.4	124	338	297	1205	352	295	2426	246	3290	3086	3675
Fe	17800	34400	47800	16800	19700	13900	23700	7140	51600	53200	38600	37900	46100	33800
Co	2.05	1.32	3.40	2.25	1.60	1.74	6.52	1.60	9.28	14.8	3.21	11.6	11.9	9.75
Cu	9.44	19.8	5.69	10.8	17.3	4.22	13.3	11.5	15.5	27.4	12.3	25.1	27.5	21.6
Zn	16.6	26.5	48.3	17.8	31.8	21.5	37.5	30.7	85.3	86.2	52.5	76.1	93.1	95.3
Rb	120	30.5	22.1	98.0	31.5	42.9	30.9	23.7	31.0	108	67.7	62.8	61.1	66.6
Sr	9.24	0.65	6.89	5.99	2.10	17.6	1.68	3.63	18.5	103	27.8	99.9	68.3	69.2
Y	3.48	0.764	0.602	2.40	1.53	1.50	0.505	0.912	3.98	9.44	2.86	6.70	3.38	2.76
Zr	281	297	469	264	300	452	482	376	327	415	453	391	500	478
Nb	42.3	25.2	39.2	42.9	20.0	31.9	46.9	22.7	29.3	24.0	25.0	16.8	19.5	14.6
Mo	5.07	4.97	4.99	4.54	1.41	1.14	3.47	1.00	3.81	0.250	5.88	-6.52E-02	-5.23E-02	-0.14
Cd	0.108	0.230	0.240	4.65E-02	0.295	0.255	0.214	0.233	0.145	0.279	0.191	0.354	0.288	0.235
Sn	14.8	22.6	14.1	14.6	14.5	7.39	14.1	6.82	15.7	5.83	8.53	4.26	5.30	4.08
Sb	3.25E-02	0.209	9.18E-02	0.111	0.118	0.136	0.313	0.178	0.139	0.104	0.298	9.17E-02	4.75E-02	5.99E-02
Cs	16.7	8.51	4.38	6.01	6.10	5.20	8.14	4.84	1.85	6.96	2.83	5.34	3.43	3.51
Ba	200	17.7	48.5	77.8	48.7	134	30.8	70.4	76.6	478	185	415	403	504
La	8.71	1.08	0.476	9.14	1.49	0.431	0.382	0.523	7.60	21.8	8.93	11.9	4.19	3.81
Ce	21.4	2.63	1.27	22.9	3.58	1.20	0.981	1.27	25.1	39.3	13.2	25.1	9.34	8.75
Pr	2.51	0.360	2.31E-03	2.51	0.420	-0.144	0.127	0.153	1.87	4.93	1.95	2.84	0.570	0.498
Nd	8.58	1.29	0.27	9.08	1.51	0.289	0.509	0.695	6.96	18.0	6.53	11.0	3.13	2.84
Sm	2.20	0.276	0.249	1.71	0.251	0.169	0.141	0.115	1.43	3.45	1.27	2.16	0.835	0.630
Eu	0.552	-1.21E-02	0.213	6.22E-02	-2.01E-02	3.46E-02	-2.90E-02	-1.86E-02	0.163	0.565	0.147	0.331	7.18E-02	1.91E-02
Gd	1.59	0.121	0.283	1.00	0.196	0.170	6.73E-02	0.101	1.04	2.35	0.753	1.67	0.660	0.518
Tb	0.625	2.07E-02	0.213	0.174	3.89E-02	6.08E-02	1.01E-02	1.05E-02	0.209	0.417	0.159	0.267	8.44E-02	6.07E-02
Dy	1.47	0.243	0.437	0.758	0.347	0.400	0.128	0.172	1.35	2.45	0.868	1.69	0.797	0.655
Ho	0.555	3.52E-02	0.261	0.149	8.88E-02	0.119	2.95E-02	4.27E-02	0.247	0.454	0.190	0.300	0.138	0.101
Er	1.03	0.143	0.355	0.436	0.328	0.402	9.12E-02	0.165	0.775	1.41	0.560	1.05	0.511	0.398
Tm	0.523	1.76E-02	0.209	7.81E-02	5.70E-02	0.103	1.47E-02	2.74E-02	0.117	0.196	0.112	0.131	5.80E-02	3.44E-02
Yb	1.03	0.20	0.449	0.461	0.502	0.621	0.280	0.401	0.920	1.38	0.783	1.06	0.718	0.519
Lu	0.440	2.07E-02	0.298	9.42E-02	7.53E-02	0.097	1.96E-02	3.25E-02	0.127	0.193	0.130	0.129	6.74E-02	3.40E-02
Hf	9.20	10.7	14.8	8.79	10.6	14.2	17.3	13.3	10.2	11.1	13.5	10.4	12.4	12.3
Tl	1.59	1.00	1.06	1.13	0.862	0.982	1.53	0.793	0.893	0.988	0.835	0.686	0.720	0.575
Pb	39.2	52.1	35.7	31.0	29.9	27.9	50.0	26.2	35.7	29.8	34.4	29.0	20.8	20.8
Bi	1.64	8.02	0.352	1.76	2.67	0.123	1.33	0.391	0.962	0.143	0.949	7.87E-02	2.95E-02	5.44E-02
Th	17.3	1.97	3.14	25.3	2.11	2.55	1.42	1.34	22.2	14.8	12.9	9.32	5.41	3.84
U	9.84	8.44	5.87	12.45	7.03	5.92	7.49	5.31	22.7	9.85	14.5	6.46	6.61	5.14

Appendix 8b: Soil type 2 samples measured elemental concentration data (mg/kg) (continued).

Geo code (500k)	Dgrr					
Geo code (25k)	Dgne					
Batch no. (n)	1	1	1 (1), 4 (3)	1	1	1
Tube ID	34	36	38; 13, 14, 15	35	37	39
Sample ID	2.9 sub	2.10 sub	2.11 sub (av)	2.9 top	2.10 top	2.11 top
Al	32800	40900	47300	23400	28600	46700
Sc	4.95	3.81	7.08	3.42	3.28	7.06
Ti	6390	6560	8390	5900	3930	6100
V	89.2	59.7	123	87.6	29.3	85.8
Cr	28.0	30.2	54.2	33.3	14.8	47.0
Mn	630	195	788	365	225	2910
Fe	42000	22800	68300	41100	9540	44900
Co	3.41	5.77	14.4	4.61	2.54	11.1
Cu	22.8	4.20	22.8	22.4	4.25	22.3
Zn	42.3	33.2	97.6	42.5	23.1	77.1
Rb	14.9	56.0	33.7	15.6	63.9	58.5
Sr	20.5	62.2	41.9	16.8	79.9	107
Y	1.27	2.42	2.13	1.68	4.28	5.74
Zr	281	426	255	252	379	309
Nb	25.6	21.4	27.5	23.1	12.8	19.9
Mo	1.48	0.87	0.237	1.92	0.108	0.276
Cd	0.182	0.206	0.213	0.265	0.131	0.235
Sn	7.89	3.76	3.88	5.97	2.17	2.99
Sb	0.112	5.17E-02	0.151	0.206	0.110	8.55E-02
Cs	4.24	3.20	1.81	4.69	2.34	5.79
Ba	159	614	263	158	626	533
La	1.97	3.93	3.22	2.26	3.17	7.36
Ce	7.18	6.87	13.5	8.40	6.04	20.8
Pr	0.191	3.07	0.815	0.293	1.21	1.48
Nd	1.52	4.86	3.12	2.03	3.22	6.38
Sm	0.304	2.94	0.819	0.452	1.59	1.56
Eu	1.49E-03	2.03	0.165	2.78E-03	1.08	0.292
Gd	0.211	2.00	0.587	0.337	1.22	1.29
Tb	1.57E-02	1.72	0.168	2.92E-02	0.882	0.269
Dy	0.321	2.64	0.782	0.442	1.49	1.51
Ho	4.45E-02	2.18	0.194	6.57E-02	0.884	0.323
Er	0.237	2.56	0.506	0.286	1.26	0.960
Tm	1.02E-02	1.98	0.122	1.61E-02	0.764	0.183
Yb	0.358	2.15	0.54	0.370	1.42	0.977
Lu	2.39E-02	1.54	0.130	1.02E-02	0.761	0.190
Hf	8.67	12.2	7.43	7.96	10.5	8.43
Tl	0.705	0.658	0.580	0.596	0.443	0.566
Pb	28.2	24.1	26.9	29.0	22.0	20.9
Bi	0.759	0.395	0.275	0.716	0.152	0.157
Th	3.52	3.36	6.80	3.42	2.86	6.25
U	4.65	4.35	5.05	4.17	3.32	3.89

Appendix 8c: Soil type 3 samples measured elemental concentration data (mg/kg) (continued overleaf).

Geo code (500k)	ODsm																		
Geo code (25k)	ODq								ODqp										ODqm
Batch no. (n)	2	2	2	2	2	2 (3), 4 (3)	2	2	2	2	2	2	2	2	2 (1), 4 (3)	2	2	2	2
Tube ID	23	27	31	33	24	28, 29, 30; 40, 41, 42	32	34	25	35	37	39	41	26	36; 46, 47, 48	38	40	42	43
Sample ID	3.10 sub	3.12 sub	3.13 sub	3.14 sub	3.10 top	3.12 top (av)	3.13 top	3.14 top	3.11 sub	3.15 sub	3.16 sub	3.17 sub	3.18 sub	3.11 top	3.15 top (av)	3.16 top	3.17 top	3.18 top	3.19 sub
Al	27000	9860	5590	28200	18100	5430	4720	22200	26600	9940	11000	26200	15800	11800	14000	8990	22200	12700	19000
Sc	4.97	2.30	2.40	5.44	3.23	2.06	1.96	4.77	5.16	3.09	2.72	5.08	3.35	2.95	3.87	1.76	4.58	3.38	3.73
Ti	3650	974	1010	4840	4260	2700	3690	4260	4340	1200	3530	5670	1470	1590	3710	3870	4020	3920	4660
V	103	24.8	11.7	105	63.0	12.7	11.2	76.3	113	18.4	51.6	73.8	43.6	37.4	35.9	34.4	58.7	33.8	67.0
Cr	95.6	31.0	13.4	76.3	55.2	9.94	8.83	53.2	137	28.1	47.2	65.1	47.4	55.0	37.0	24.9	60.5	28.4	62.6
Mn	43.4	26.6	27.0	528	126	50.3	43.0	764	41.8	21.0	31.1	63.9	37.2	77.6	48.7	41.9	72.4	833	255
Fe	17900	4180	1940	39100	12300	1560	1700	22300	31300	3970	5290	14400	9590	9910	10000	4270	14600	6890	14800
Co	2.16	0.763	0.544	7.33	3.16	0.452	0.469	3.73	2.09	0.621	1.06	2.04	1.16	1.07	0.976	0.802	1.57	1.21	1.73
Cu	11.2	3.26	7.62	34.5	11.8	6.75	7.34	12.6	7.09	3.61	3.33	7.03	4.72	7.23	7.60	6.95	8.17	12.8	10.3
Zn	28.6	6.79	15.8	64.9	33.4	5.43	4.79	33.5	10.3	5.52	8.91	18.9	8.87	9.04	12.2	12.1	19.0	12.6	15.1
Rb	26.3	19.9	9.39	11.8	49.8	15.3	8.74	25.7	15.4	19.2	13.6	29.2	25.5	18.1	26.0	13.6	25.5	27.3	51.7
Sr	10.3	6.03	11.2	5.34	19.0	21.8	24.9	21.3	4.65	6.70	3.93	10.9	11.0	12.2	13.7	14.3	13.2	39.6	12.4
Y	1.33	10.0	10.8	1.08	5.44	8.60	9.90	3.93	0.914	12.4	6.22	5.33	2.76	5.32	10.3	3.99	5.10	8.28	5.33
Zr	154	278	224	129	163	165	146	122	208	367	292	275	171	203	216	175	260	150	203
Nb	14.7	1.35	0.67	15.0	7.43	5.35	3.63	12.2	12.5	1.86	6.13	12.9	6.41	3.60	9.18	8.56	12.3	11.1	8.95
Mo	-0.105	0.145	-0.175	4.18E-01	7.84E-02	4.18E-02	-8.72E-02	0.176	0.252	-0.203	-1.98E-02	0.798	-9.13E-02	0.302	3.49E-02	0.341	0.273	3.43E-02	0.276
Cd	0.100	6.94E-02	0.103	7.31E-02	8.48E-02	5.27E-02	2.83E-02	0.359	6.02E-02	0.168	0.160	6.65E-02	4.52E-02	0.106	0.139	5.28E-02	0.115	9.06E-02	5.13E-02
Sn	3.77	0.835	0.362	4.52	4.07	0.704	0.515	3.08	4.56	0.802	2.96	3.52	1.80	1.31	1.95	1.62	2.62	2.10	3.80
Sb	2.73	5.03E-02	-7.02E-03	0.505	1.94	0.154	0.104	0.266	0.658	0.446	0.162	0.604	0.303	0.236	1.19	7.59E-02	0.622	0.399	0.150
Cs	1.67	2.96	1.21	1.12	2.25	1.92	0.83	2.54	1.73	2.41	1.52	2.13	1.91	1.45	1.91	2.43	1.47	2.41	1.56
Ba	117	26.3	52.9	38.2	321	82.7	65.3	285	20.4	123	19.6	109	43.6	52.0	178	118	150	211	236
La	1.32	14.3	17.1	1.05	9.67	17.0	12.3	4.41	0.730	17.4	6.57	6.55	1.15	4.72	19.9	5.79	7.66	6.45	14.6
Ce	3.18	30.7	29.7	2.58	20.6	32.2	24.1	11.0	1.59	36.8	15.0	14.7	2.66	10.4	43.7	11.4	18.1	14.2	33.1
Pr	0.438	3.69	3.78	0.327	2.55	3.93	2.70	1.40	0.215	4.54	1.87	2.11	0.328	1.40	5.19	1.48	2.54	1.71	3.89
Nd	1.68	13.8	13.7	1.31	9.17	14.2	10.0	5.65	0.892	16.9	7.28	8.35	1.37	5.30	19.3	5.61	9.68	6.25	14.2
Sm	0.309	2.75	2.51	0.239	1.75	2.65	1.77	1.18	0.162	3.31	1.34	1.78	0.220	1.11	3.46	1.05	2.13	1.24	2.30
Eu	3.02E-02	0.338	0.365	1.84E-02	0.219	0.352	0.286	0.177	1.49E-02	0.480	0.232	0.293	4.06E-02	0.181	0.508	0.144	0.296	0.218	0.355
Gd	0.226	1.98	1.86	0.166	1.13	1.82	1.36	0.822	0.135	2.52	1.10	1.31	0.298	0.871	2.43	0.671	1.39	1.22	1.62
Tb	4.39E-02	0.370	0.338	3.89E-02	0.213	0.310	0.293	0.173	3.03E-02	0.460	0.195	0.264	8.02E-02	0.209	0.425	0.124	0.256	0.252	0.241
Dy	0.374	2.10	2.00	0.329	1.32	1.67	1.87	1.13	0.283	2.64	1.37	1.63	0.771	1.32	2.43	0.777	1.59	1.86	1.31
Ho	7.76E-02	0.477	0.386	6.25E-02	0.274	0.324	0.405	0.225	5.44E-02	0.602	0.305	0.349	0.175	0.286	0.465	0.168	0.338	0.414	0.258
Er	0.231	1.39	1.15	0.246	0.837	0.910	1.16	0.693	0.192	1.74	1.04	1.08	0.565	0.910	1.39	0.649	1.00	1.18	0.645
Tm	3.89E-02	0.232	0.176	2.44E-02	0.112	0.141	0.191	0.104	2.53E-02	0.258	0.156	0.192	0.097	0.152	0.196	8.28E-02	0.175	0.193	0.125
Yb	0.350	1.487	1.249	0.248	0.838	1.03	1.33	0.807	0.287	1.80	1.24	1.25	0.733	1.06	1.52	0.671	1.24	1.33	0.785
Lu	4.59E-02	0.230	0.205	2.91E-02	0.103	0.155	0.213	0.134	2.84E-02	0.293	0.185	0.199	0.109	0.179	0.208	7.94E-02	0.228	0.185	0.140
Hf	4.42	8.03	6.41	3.74	4.76	4.96	4.45	3.54	6.57	10.9	8.70	7.82	4.96	5.59	6.27	5.35	7.82	4.47	5.99
Tl	0.931	0.305	5.23E-02	0.742	0.494	7.10E-02	2.22E-02	0.615	0.846	0.286	0.354	0.830	0.604	0.424	0.258	0.420	0.620	0.322	0.434
Pb	17.4	3.21	5.20	15.3	26.3	5.23	5.36	15.0	12.1	6.74	9.07	17.0	5.36	9.56	10.6	10.6	15.9	8.03	15.6
Bi	0.245	0.303	5.10E-02	0.257	0.143	8.73E-02	2.53E-02	0.158	0.145	3.92E-02	5.77E-02	0.598	0.161	0.524	5.37E-02	2.31E-02	0.309	0.122	0.126
Th	2.30	6.77	5.86	1.40	6.85	6.58	4.77	3.80	1.77	9.01	3.88	4.87	1.23	3.09	10.3	2.62	7.05	3.74	9.62
U	2.88	2.99	2.46	2.30	2.98	2.03	1.88	1.99	2.35	4.04	3.28	3.14	1.65	1.97	3.37	2.22	3.23	1.80	3.76

Appendix 8c: Soil type 3 samples measured elemental concentration data (mg/kg) (continued).

Geo code (500k)	ODsm									Psp											
Geo code (25k)	ODqm									Plb						Pus		Pfs			
Batch no. (n)	2	2	2 (1), 4 (3)	3	2	2	2	2	3	1	1	1	1	1	1	1	1	4 (3)	3	4 (3)	3
Tube ID	45	47	49; 43 44 45	10	44	46	48	50	11	40	42	44	41	43	47	45	46	34, 35, 36	12	37, 38, 39	13
Sample ID	3.20 sub	3.21 sub	3.22 sub (av)	3.23 sub	3.19 top	3.20 top	3.21 top	3.22 top	3.23 top	3.4 sub	3.6 sub	3.7 sub	3.4 top	3.6 top	3.7 top	3.8 sub	3.8 top	3.9 sub (av)	3.26 sub	3.9 top (av)	3.26 top
Al	10900	34000	17000	38000	18300	5480	12900	10800	26700	28500	51100	42400	23100	16700	34000	14600	8320	25400	29900	7120	14300
Sc	2.45	3.34	4.30	5.46	3.38	1.52	2.00	2.48	4.45	4.09	3.64	6.76	4.02	1.89	6.38	2.63	2.09	4.97	3.59	1.39	2.31
Ti	1300	5570	3680	4470	4020	1330	2360	3800	3360	4180	5330	4890	3880	3010	4290	2710	4370	6620	2890	2250	3410
V	18.6	127	41.1	103	55.8	12.3	49.7	35.7	71.1	76.8	88.1	80.6	54.5	34.8	92.7	30.4	18.5	93.5	40.1	23.4	24.5
Cr	35.7	102	41.6	69.7	52.2	25.9	48.2	34.3	41.8	63.9	71.8	55.9	52.0	24.9	46.1	20.5	13.3	58.3	38.3	21.1	20.4
Mn	18.8	74.5	1185	177	296	229	192	933	262	18.6	29.9	108	32.9	38.5	160	190	256	70.7	29.4	91.2	65.6
Fe	1980	49100	8830	34000	13200	1560	17800	7360	18100	26000	5590	18800	7960	4470	40600	8650	3870	26700	6520	6230	3550
Co	0.361	2.53	2.15	3.07	1.15	0.606	2.58	2.52	1.64	1.18	0.989	5.61	0.912	0.677	8.43	1.32	1.34	4.23	1.11	1.34	2.82
Cu	4.99	6.46	22.0	24.0	6.47	4.89	7.83	5.68	13.1	6.16	3.06	6.48	5.20	7.36	13.7	7.94	8.79	6.39	5.61	5.99	15.2
Zn	5.36	18.2	24.7	33.0	11.6	5.22	19.2	15.1	16.0	15.7	7.57	12.0	16.1	18.5	20.8	19.5	17.9	13.3	7.57	7.12	8.98
Rb	13.8	10.2	46.7	20.1	44.6	5.16	29.6	42.8	67.3	24.5	35.2	16.9	35.6	14.4	8.57	31.5	24.7	12.6	24.4	21.2	23.5
Sr	18.4	5.59	21.4	11.3	10.9	16.0	10.6	16.2	20.1	72.9	154	91.1	38.4	48.7	46.1	19.7	21.5	9.9	22.5	17.1	19.1
Y	8.00	1.93	11.5	2.92	5.51	6.77	4.80	6.63	4.94	10.0	9.81	8.76	12.8	5.21	8.19	9.58	9.75	6.34	9.16	3.86	7.61
Zr	257	154	309	124	186	220	138	224	97.4	223	229	208	267	120	161	147	114	275	268	163	241
Nb	1.81	17.9	7.28	14.9	12.2	1.20	3.48	5.98	11.3	12.0	15.0	12.1	11.9	8.19	10.4	3.64	7.50	17.2	10.1	3.39	8.12
Mo	4.75	0.959	-0.906	2.51	0.243	-0.120	-0.195	4.03E-02	1.16	0.199	7.57	0.351	-7.97E-02	2.29	0.442	-0.497	1.73E-02	1.18	0.431	0.370	0.522
Cd	0.147	6.13E-02	4.54E-02	6.93E-02	0.121	6.80E-02	5.47E-02	0.106	6.28E-02	4.83E-02	5.04E-02	6.37E-02	7.15E-02	0.139	4.16E-02	0.104	0.184	0.096	8.44E-02	5.27E-02	0.118
Sn	0.84	4.63	2.50	4.25	3.39	0.419	1.60	1.66	3.73	3.97	7.70	3.96	3.04	2.35	2.58	0.963	1.03	3.40	3.14	0.981	2.14
Sb	0.186	1.29	0.412	0.222	0.250	0.188	0.303	0.271	0.099	0.665	0.675	0.197	0.885	0.216	0.232	9.13E-02	0.100	0.544	0.233	0.163	0.156
Cs	2.26	2.55	2.51	1.52	1.07	1.13	1.41	2.24	3.29	6.68	1.78	2.24	6.56	2.32	2.41	5.68	4.44	0.58	1.94	1.26	2.01
Ba	125.41	60.1	159	170	231	83.7	87.2	206	354	91.3	82.0	156	115	129	130	125	120	45.0	46.1	116	99.2
La	17.5	3.76	26.5	4.72	20.0	15.2	12.6	20.0	18.1	10.8	27.7	13.9	12.6	12.2	13.3	23.1	19.2	11.4	11.8	14.4	12.9
Ce	34.9	10.1	56.7	12.6	41.5	27.1	28.0	41.1	39.8	25.4	58.1	30.8	29.3	21.7	25.9	46.4	38.6	26.5	27.1	28.6	23.8
Pr	4.19	1.18	6.69	1.45	4.77	3.57	3.21	4.86	4.20	3.04	7.54	3.68	3.40	2.69	3.05	5.07	4.07	3.14	3.28	3.31	2.97
Nd	15.4	4.55	25.0	5.63	16.6	12.9	11.9	16.5	15.2	12.2	30.5	15.0	13.8	10.3	12.9	18.7	16.1	11.7	12.8	11.9	11.4
Sm	2.79	0.853	4.38	1.10	2.85	2.33	2.17	2.83	2.36	2.68	5.48	3.03	2.71	1.64	2.37	3.56	3.03	2.30	2.44	1.99	2.02
Eu	0.347	0.109	0.626	0.178	0.400	0.246	0.199	0.394	0.292	0.514	0.955	0.552	0.461	0.321	0.382	0.392	0.316	0.233	0.271	0.129	0.118
Gd	1.85	0.506	2.90	0.820	1.72	1.46	1.37	1.85	1.44	2.11	2.83	2.13	2.15	1.02	1.80	2.21	2.03	1.47	1.71	1.27	1.50
Tb	0.291	9.05E-02	0.456	0.128	0.250	0.220	0.184	0.285	0.240	0.473	0.476	0.412	0.429	0.237	0.284	0.384	0.297	0.261	0.325	0.173	0.226
Dy	1.64	0.551	2.54	0.815	1.38	1.38	1.09	1.44	1.17	2.50	2.33	2.14	2.84	1.04	1.85	1.90	1.81	1.58	2.25	0.901	1.48
Ho	0.358	0.111	0.492	0.183	0.252	0.248	0.205	0.283	0.196	0.586	0.500	0.466	0.608	0.285	0.347	0.386	0.327	0.306	0.456	0.155	0.301
Er	0.933	0.346	1.44	0.506	0.736	0.668	0.639	0.72	0.571	1.66	1.40	1.33	1.82	0.758	1.16	1.09	1.03	0.962	1.27	0.447	0.828
Tm	0.129	4.83E-02	0.210	8.95E-02	9.83E-02	0.114	9.05E-02	0.111	9.49E-02	0.384	0.271	0.245	0.316	0.184	0.146	0.209	0.141	0.137	0.208	5.08E-02	0.129
Yb	1.17	0.370	1.62	0.610	0.724	0.881	0.733	0.789	0.608	1.84	1.67	1.43	1.99	0.856	1.19	1.16	1.22	1.17	1.53	0.413	0.867
Lu	0.147	5.46E-02	0.248	7.84E-02	0.122	0.128	8.10E-02	0.117	7.79E-02	0.344	0.271	0.243	0.328	0.198	0.141	0.214	0.141	0.167	0.243	5.70E-02	0.150
Hf	7.38	4.80	8.76	3.93	5.50	6.75	4.29	6.62	3.15	6.56	6.57	6.37	8.12	3.65	4.99	4.39	3.46	7.83	9.19	5.03	8.05
Tl	0.138	0.363	0.298	0.576	0.392	5.09E-02	0.298	0.408	0.381	0.619	0.401	0.250	0.556	0.162	0.235	0.193	0.164	0.215	0.598	0.167	0.279
Pb	6.89	14.6	30.5	27.9	12.8	6.63	11.8	31.0	18.7	12.8	39.7	10.3	10.8	15.4	15.2	7.36	6.41	11.5	10.3	9.61	8.49
Bi	3.81E-02	0.328	7.60E-02	0.860	0.129	2.96E-02	0.123	7.06E-02	0.515	0.113	0.127	-2.64E-02	3.19E-02	1.2E-02	-1.22E-02	-2.72E-02	-6.07E-02	0.285	0.171	0.170	0.122
Th	7.61	10.3	10.9	6.65	10.8	5.42	9.48	7.74	10.7	5.94	11.3	8.12	6.89	3.53	5.85	7.67	6.72	12.0	8.56	8.08	5.79
U	3.72	3.14	4.58	2.94	3.10	2.98	2.73	3.24	2.54	2.79	6.05	2.56	3.01	2.81	2.00	2.11	1.98	3.68	3.86	2.22	3.00

Appendix 8d: Soil type 4 samples measured elemental concentration data (mg/kg) (continued overleaf).

Geo code (500k)	Qa												Qrc					
Geo code (25k)	Qha												Qha					
Batch no. (n)	3	3 (1), 4 (3)	3	3	3	3 (3)	3	3	3	3	3	3	3	3	3	3 (1), 4 (3)	3	3
Tube ID	14	16; 25, 26, 27	18	20	22	24, 25, 26	15	17	19	21	23	27	28	30	32	29; 28, 29, 30	31	33
Sample ID	4.3 sub	4.4 sub (av)	4.5 sub	4.6 sub	4.7 sub	4.8 sub (av)	4.3 top	4.4 top	4.5 top	4.6 top	4.7 top	4.8 top	4.9 sub	4.11 sub	4.12 sub	4.9 top (av)	4.11 top	4.12 top
Al	38200	28200	25000	38500	47100	7120	32000	28600	23600	38400	45100	6170	14600	26900	44200	6120	13400	54600
Sc	4.62	4.76	5.55	9.27	9.05	2.88	4.19	4.03	4.83	8.34	8.33	2.46	2.71	3.47	12.7	1.94	1.72	14.1
Ti	3820	3840	2560	3700	4460	878	3660	3190	3190	3730	4060	3490	1960	1530	4260	4050	3380	3910
V	64.0	56.1	62.6	72.7	108	10.4	52.9	51.3	58.2	79.4	92.9	14.2	26.3	37.3	226	22.5	24.5	110
Cr	50.5	48.8	48.9	57.9	82.9	16.9	46.5	43.1	44.8	62.9	77.5	12.9	28.6	30.7	120	17.4	14.3	86.0
Mn	505	637	978	700	597	47.1	488	583	584	807	858	66.3	89.8	133	2137	148	187	567
Fe	29300	25300	35400	21100	38500	3040	22900	20500	19600	24400	33900	2050	8300	9500	56000	4150	5340	28900
Co	12.4	10.9	14.0	8.52	20.4	0.638	9.99	10.7	8.43	11.7	17.6	1.08	2.20	4.19	46.0	1.34	3.02	19.2
Cu	20.0	13.7	76.0	24.7	23.9	4.31	13.8	27.0	30.5	27.4	21.9	9.22	7.75	3.92	45.8	8.10	7.22	41.9
Zn	53.8	58.2	244	71.7	92.1	5.30	50.3	49.7	120	80.5	98.3	10.6	9.57	18.7	49.9	11.1	16.1	61.7
Rb	79.9	67.9	27.9	48.0	24.0	22.7	107	66.7	49.2	61.6	45.7	21.9	14.9	61.4	6.34	20.3	65.8	24.6
Sr	25.5	27.2	29.1	31.1	24.4	14.9	30.5	34.2	26.0	35.0	26.7	21.3	14.4	32.9	27.3	16.1	35.3	46.5
Y	11.6	9.63	7.37	12.6	13.7	13.4	13.0	7.25	8.83	9.04	12.7	13.4	7.61	4.33	5.65	5.80	3.84	10.3
Zr	311	369	193	145	150	256	449	214	170	123	132	191	167	208	145	148	148	136
Nb	21.2	18.8	8.70	11.4	15.5	0.667	21.0	15.1	10.1	11.7	14.6	4.86	3.33	5.29	11.7	5.24	8.20	10.6
Mo	1.94	0.732	0.594	0.416	0.769	0.436	1.33	0.862	0.670	0.574	2.93	0.194	8.28E-03	-1.2E-02	0.845	-0.500	0.138	0.663
Cd	0.307	0.334	0.322	8.18E-02	0.240	9.32E-02	0.381	0.315	0.263	0.366	0.343	7.36E-02	2.89E-02	0.167	0.152	0.111	0.156	0.206
Sn	7.91	6.82	2.40	2.86	4.76	0.416	7.55	5.07	2.16	2.90	4.43	0.823	0.857	1.25	2.17	0.984	1.19	1.86
Sb	0.139	0.140	8.61	0.316	0.511	4.45E-02	0.238	0.193	2.44	0.484	0.446	0.161	0.188	0.233	0.385	0.181	0.374	0.411
Cs	7.06	4.60	2.65	4.22	2.09	1.94	9.23	5.96	3.28	5.19	5.20	1.39	1.27	1.47	0.82	1.61	1.47	1.64
Ba	288	281	269	341	187	91	306	329	289	374	281	99.1	89.7	281	364	107	384	392
La	31.9	24.5	12.2	20.4	16.5	24.6	41.9	17.4	19.9	17.5	20.9	21.8	17.7	8.78	7.77	15.7	8.94	18.2
Ce	61.1	48.3	28.2	37.7	36.7	48.0	82.4	33.6	44.5	34.3	40.1	43.0	35.0	19.9	20.3	32.4	17.4	38.2
Pr	7.76	6.33	3.93	5.53	5.58	5.69	9.96	4.29	5.49	4.72	5.96	4.99	4.02	2.24	2.57	3.63	1.86	5.05
Nd	27.9	23.2	16.2	21.8	23.0	20.9	36.4	16.1	20.8	17.7	22.5	18.4	14.9	8.09	10.7	13.3	6.72	19.5
Sm	5.02	4.29	3.21	4.26	4.70	3.74	6.36	2.86	4.09	3.35	4.17	3.35	2.92	1.59	2.22	2.30	1.24	3.93
Eu	0.335	0.342	0.534	0.740	0.822	0.456	0.338	0.252	0.566	0.520	0.783	0.407	0.246	0.271	0.418	0.216	0.190	0.888
Gd	3.32	2.84	2.36	3.05	3.79	2.55	3.96	1.96	2.54	2.34	3.33	2.33	1.69	0.906	1.65	1.51	0.729	2.65
Tb	0.552	0.453	0.360	0.489	0.625	0.446	0.588	0.337	0.385	0.384	0.533	0.416	0.255	0.141	0.272	0.221	0.105	0.446
Dy	3.08	2.46	2.24	3.03	3.65	2.50	3.16	1.92	2.23	2.21	3.32	2.49	1.49	0.902	1.68	1.23	0.791	2.81
Ho	0.578	0.464	0.468	0.570	0.785	0.489	0.605	0.321	0.421	0.452	0.615	0.518	0.296	0.218	0.326	0.225	0.145	0.518
Er	1.57	1.34	1.30	1.73	2.05	1.52	1.55	0.98	1.19	1.37	1.74	1.46	0.97	0.641	0.954	0.622	0.418	1.43
Tm	0.246	0.194	0.190	0.237	0.308	0.240	0.263	0.154	0.200	0.174	0.243	0.249	0.111	0.093	0.131	9.32E-02	7.65E-02	0.230
Yb	1.96	1.56	1.44	1.80	2.17	1.79	2.06	1.16	1.31	1.33	1.65	1.70	1.08	0.880	0.939	0.731	0.642	1.45
Lu	0.269	0.240	0.220	0.232	0.277	0.286	0.322	0.167	0.182	0.165	0.248	0.284	0.149	0.111	0.119	0.105	6.91E-02	0.199
Hf	10.7	11.2	5.57	4.36	4.61	7.93	14.2	6.90	4.88	3.65	4.18	6.01	4.86	6.25	4.40	4.10	4.64	4.09
Tl	1.15	0.771	0.555	0.695	1.11	0.136	1.07	0.871	0.574	0.701	1.13	0.111	0.256	0.740	0.402	0.119	0.403	0.357
Pb	35.1	27.7	334	10.9	24.5	4.78	33.7	24.8	104	14.4	22.8	4.63	9.68	18.9	15.5	6.87	17.3	14.6
Bi	1.15	0.71	1.30	0.17	0.33	0.17	0.92	0.50	0.38	0.22	1.05	0.06	0.08	0.11	0.10	0.05	0.04	0.13
Th	29.7	22.5	8.62	10.2	12.9	10.4	36.5	14.3	10.9	9.84	10.8	8.74	8.15	7.38	5.15	6.61	4.64	7.51
U	22.0	15.0	3.16	4.58	6.76	3.22	18.6	10.4	3.36	4.30	7.13	2.72	2.19	2.70	2.81	2.02	2.05	2.64

Appendix 8d: Soil type 4 samples measured elemental concentration data (mg/kg) (continued).

Geo code (500k)	Qa											
Geo code (25k)	Qpao											
Batch no. (n)	3	3	3	3	3	3	3 (1), 4 (3)	3	3	3	3	3
Tube ID	34	36	38	40	42	44	35; 31, 32, 33	37	39	41	43	45
Sample ID	4.13 sub	4.14 sub	4.15 sub	4.16 sub	4.18 sub	4.19 sub	4.13 top (av)	4.14 top	4.15 top	4.16 top	4.18 top	4.19 top
Al	33400	11400	13700	14000	11000	16600	27500	11200	10700	6650	13400	13500
Sc	3.27	1.42	4.12	3.27	1.33	4.02	2.72	1.00	2.06	1.62	1.42	1.95
Ti	4780	2630	1130	1130	2590	2320	3740	3520	1460	3600	2660	4000
V	69.2	37.4	23.5	24.2	49.9	65.0	51.8	39.9	34.6	17.5	53.5	62.1
Cr	40.9	37.3	28.1	25.8	28.3	52.3	30.4	28.0	28.6	13.6	28.4	37.6
Mn	300	130	216	47.1	530	492	404	223	741	116	674	717
Fe	32400	8930	9880	8090	11800	21800	25600	8290	11500	3090	12500	16100
Co	4.55	6.16	5.95	0.866	13.1	15.8	4.29	5.90	6.59	0.611	10.1	14.0
Cu	7.14	7.37	10.0	6.45	10.7	23.7	10.4	10.5	14.6	9.42	10.7	18.9
Zn	24.9	12.8	19.2	7.56	37.3	88.5	35.2	16.0	17.8	5.23	48.7	93.3
Rb	123	23.1	25.4	55.7	37.0	47.6	92.7	28.8	29.8	18.8	57.3	57.5
Sr	21.7	36.5	13.1	11.5	31.9	24.2	30.9	41.3	13.5	18.5	35.9	24.9
Y	4.74	1.50	9.20	12.7	2.04	2.79	3.54	1.71	6.00	6.06	1.66	2.36
Zr	341	197	177	148	137	180	367	154	147	103	127	138
Nb	29.5	2.46	0.959	1.60	2.32	3.97	23.0	3.21	2.27	4.62	3.62	3.96
Mo	2.61	1.83	0.281	0.189	0.215	-8.42E-03	1.03	0.740	0.290	2.06E-02	0.426	0.288
Cd	0.188	0.127	4.65E-02	0.100	0.179	0.175	0.163	0.161	4.06E-02	7.26E-03	0.216	0.618
Sn	9.47	0.46	0.63	0.56	0.73	0.88	7.22	0.41	0.58	0.86	0.356	0.982
Sb	0.227	0.129	0.115	0.101	0.185	0.135	0.140	0.145	0.154	0.253	9.48E-02	0.162
Cs	7.60	1.41	2.57	5.40	1.22	1.38	3.89	1.12	2.05	2.32	1.34	2.20
Ba	282	305	107	107	366	325	247	296	146	101	378	337
La	11.3	5.47	19.1	19.1	4.64	7.53	10.9	6.66	15.4	12.8	6.57	6.60
Ce	25.1	12.4	34.3	39.2	9.99	15.9	27.4	14.1	28.2	22.5	13.2	14.5
Pr	3.08	1.60	4.36	4.59	1.23	1.91	2.73	1.68	3.49	2.88	1.43	1.60
Nd	11.0	5.90	16.2	16.9	4.60	7.14	9.65	6.11	12.8	10.7	5.29	6.23
Sm	2.07	1.03	2.83	3.27	0.74	1.20	1.72	1.00	2.16	1.66	0.808	0.984
Eu	0.123	4.53E-02	0.408	0.479	0.104	0.117	8.00E-02	8.30E-02	0.304	0.235	9.16E-02	0.105
Gd	1.30	0.586	1.97	2.40	0.517	0.700	1.04	0.596	1.55	1.18	0.510	0.707
Tb	0.215	7.16E-02	0.342	0.403	7.58E-02	0.116	0.159	8.26E-02	0.234	0.204	6.55E-02	0.103
Dy	1.32	0.457	1.79	2.44	0.469	0.660	0.943	0.478	1.24	1.21	0.415	0.530
Ho	0.255	8.64E-02	0.345	0.520	7.70E-02	0.113	0.174	7.79E-02	0.229	0.232	7.07E-02	0.102
Er	0.871	0.234	0.948	1.54	0.277	0.429	0.535	0.211	0.664	0.666	0.221	0.311
Tm	0.121	3.79E-02	0.166	0.240	4.01E-02	3.85E-02	7.72E-02	2.67E-02	8.48E-02	0.099	2.90E-02	3.87E-02
Yb	0.989	0.320	1.09	1.63	0.333	0.391	0.806	0.282	0.570	0.704	0.227	0.307
Lu	0.142	4.23E-02	0.152	0.233	5.41E-02	5.08E-02	0.115	3.52E-02	9.44E-02	0.110	1.98E-02	2.95E-02
Hf	11.3	5.23	4.95	4.43	3.73	5.20	11.6	4.32	4.13	3.30	3.75	3.91
Tl	1.28	0.353	0.207	0.302	0.365	0.420	0.617	0.371	0.232	0.161	0.314	0.315
Pb	29.1	9.92	12.3	5.27	10.9	12.3	29.8	9.45	11.7	6.06	12.0	13.5
Bi	1.01	0.472	0.175	9.11E-02	6.91E-02	1.07E-02	0.718	0.254	0.119	4.79E-02	4.50E-02	3.84E-02
Th	21.4	3.90	6.46	7.48	3.22	4.78	21.3	3.82	5.36	4.46	3.47	3.67
U	15.6	1.83	2.56	2.46	1.92	1.97	10.8	1.81	2.11	1.76	2.24	1.97

Appendix 9: Soil samples weight loss on ignition results (continued overleaf).

Soil type 1

Geo code (500k)	Qrc												Jdtm											
Geo code (25k)	Qptd												Jd											
Batch no.	4	1	1	1, 5	1	1, 5	4	1	1	1	Trial, 1	1	1	4	4	1	4	4						
Crucible ID	14	1	5	7; 1	9	11; 2	15	2	6	8	1, 2, 3; 10	12	3	16	18	4	17	19	Soil type 1		Subsoil		Topsoil	
Sample ID	1.3 sub	1.4 sub	1.9 sub	1.10 sub	1.11 sub	1.14 sub	1.3 top	1.4 top	1.9 top	1.10 top	1.11 top	1.14 top	1.7 sub	1.8 sub	1.13 sub	1.7 top	1.8 top	1.13 top	Mean	RSD (%)	Mean	RSD (%)	Mean	RSD (%)
%LOI (490°C)[a]	25.0	16.3	9.50	11.4	6.29	8.43	31.4	17.8	29.1	35.4	10.4	8.96	27.7	26.6	25.8	43.9	58.9	36.8	23.9	58	15.7	56	30.3	53
Est. % carbonates[b]	1.24	2.16	1.67	3.05	1.03	1.80	1.16	1.66	1.52	2.65	0.732	0.791	3.17	1.19	1.38	2.56	1.49	1.05	1.68	43	1.85	43	1.51	46

Soil type 2

Geo code (500k)	Dgrt								Dgrh					
Geo code (25k)	Dgaap						Dgae		Dgnv				Dgnx	
Batch no.	1	4	1	1	4	5	4	4	1	1	Trial, 1	1	1	1
Crucible ID	13	21	15	14	20	4	22	23	17	19	4, 5, 6; 18	20	21	22
Sample ID	2.1 sub	2.2 sub	2.3 sub	2.1 top	2.2 top	2.3 top	2.4 sub	2.4 top	2.5 sub	2.6 sub	2.5 top	2.6 top	2.7 sub	2.7 top
%LOI (490°C)[a]	22.4	18.4	12.3	24.9	50.0	14.30	14.9	40.0	14.3	20.4	25.3	34.6	17.2	29.6
Est. % carbonates[b]	1.55	1.36	1.39	1.51	1.21	0.662	1.20	1.16	2.21	2.43	1.95	2.53	2.13	1.67

Soil type 2 (continued)

Geo code (500k)	Dgrr											
Geo code (25k)	Dgne											
Batch no.	1	1	2	1	Trial, 2	2						
Crucible ID	23	25	2	24	7, 8, 9; 1	3	Soil type 2		Subsoil		Topsoil	
Sample ID	2.9 sub	2.10 sub	2.11 sub	2.9 top	2.10 top	2.11 top	Mean	RSD (%)	Mean	RSD (%)	Mean	RSD (%)
%LOI (490°C)[a]	39.4	4.5	13.0	35.7	15.2	27.6	23.7	48	17.7	52	29.7	37
Est. % carbonates[b]	3.42	1.84	1.53	3.09	0.431	1.84	1.76	41	1.91	35	1.61	50

Soil type 3

Geo code (500k)	ODsm																	
Geo code (25k)	ODq								ODqp									
Batch no.	2	Trial, 2	2	2	2	2	5	2	2	2	3	3	5	2	5	3	3	3, 5
Crucible ID	14	13, 14, 15; 18	20	22	15	19	7	23	16	24	1	3	9	17	8	2	4	6; 10
Sample ID	3.10 sub	3.12 sub	3.13 sub	3.14 sub	3.10 top	3.12 top	3.13 top	3.14 top	3.11 sub	3.15 sub	3.16 sub	3.17 sub	3.18 sub	3.11 top	3.15 top	3.16 top	3.17 top	3.18 top
%LOI (490°C)[a]	4.15	3.05	3.03	7.02	11.5	14.3	10.9	13.0	5.49	2.27	7.35	3.33	2.60	3.76	7.15	20.4	8.28	9.20
Est. % carbonates[b]	1.08	0.378	0.195	1.71	0.846	0.262	0.177	1.53	1.13	0.461	0.892	1.19	0.668	0.483	0.594	0.667	0.904	0.587

[a]%LOI (490°C): organic matter content (% dry sample weight) by loss on ignition at 490 °C
[b]Est. % carbonates: estimation of CO_3^{2-} content of the mineral fraction by subsequent ignition at 800°C (% dry sample weight exclusive of organic matter content).

Appendix 9: Soil samples weight loss on ignition results (continued).

Soil type 3 (continued)

Geo code (500k)	ODsm									
Geo code (25k)	ODqm									
Batch no.	3, 5	Trial, 3	3	3	3	3	3	3	3	3
Crucible ID	7; 11	16, 17, 18; 9	11	13	15	8	10	12	14	16
Sample ID	3.19 sub	3.20 sub	3.21 sub	3.22 sub	3.23 sub	3.19 top	3.20 top	3.21 top	3.22 top	3.23 top
%LOI (490°C)[a]	5.18	2.57	10.3	4.38	11.6	6.93	5.06	7.70	6.27	14.6
Est. % carbonates[b]	0.959	0.236	0.839	0.469	1.15	0.723	0.201	0.609	0.464	0.965

Soil type 3 (continued)

Geo code (500k)	Psp																	
Geo code (25k)	Plb						Pus		Pfs									
Batch no.	2	2	2	Trial, 2	2, 5	2	2	2	2	4	2	4						
Crucible ID	4	6	8	10, 11, 12; 5	7; 6	9	10	11	12	24	13	25	Soil type 3		Subsoil		Topsoil	
Sample ID	3.4 sub	3.6 sub	3.7 sub	3.4 top	3.6 top	3.7 top	3.8 sub	3.8 top	3.9 sub	3.26 sub	3.9 top	3.26 top	Mean	RSD (%)	Mean	RSD (%)	Mean	RSD (%)
%LOI (490°C)[a]	5.26	9.92	13.2	6.59	36.7	19.5	1.94	9.40	6.64	4.79	7.73	16.9	8.75	73	5.70	58	11.8	64
Est. % carbonates[b]	0.736	1.03	1.11	0.669	1.00	1.10	0.321	0.278	0.786	1.45	0.379	0.822	0.751	50	0.839	49	0.663	51

Soil type 4

Geo code (500k)	Qa												Qrc					
Geo code (25k)	Qha												Qha					
Batch no.	3	3	3	6	3	6	Trial, 3	3	3	6	3	6	3	Trial, 4	4	4	4	4
Crucible ID	17	19	21	1	23	3	19, 20, 21; 18	20	22	2	24	4	25	22, 23, 24; 2	4	1	3	5
Sample ID	4.3 sub	4.4 sub	4.5 sub	4.6 sub	4.7 sub	4.8 sub	4.3 top	4.4 top	4.5 top	4.6 top	4.7 top	4.8 top	4.9 sub	4.11 sub	4.12 sub	4.9 top	4.11 top	4.12 top
%LOI (490°C)[a]	24.1	15.8	4.80	10.1	10.4	1.43	23.1	23.5	8.05	15.6	18.0	8.42	3.56	3.69	15.3	7.42	9.74	19.9
Est. % carbonates[b]	1.35	1.10	1.19	1.16	1.60	9.63E-02	1.20	1.17	1.23	1.33	1.80	0.142	0.577	0.824	1.70	0.430	0.499	1.62

Soil type 4 (continued)

Geo code (500k)	Qa																	
Geo code (25k)	Qpao																	
Batch no.	4	4	6	4	6	4	4	4	6	4	6	4						
Crucible ID	6	8	5	10	8	12	7	8	6	11	9	13	Soil type 4		Subsoil		Topsoil	
Sample ID	4.13 sub	4.14 sub	4.15 sub	4.16 sub	4.18 sub	4.19 sub	4.13 top	4.14 top	4.15 top	4.16 top	4.18 top	4.19 top	Mean	RSD (%)	Mean	RSD (%)	Mean	RSD (%)
%LOI (490°C)[a]	15.6	1.35	2.29	2.86	4.55	5.37	44.0	7.13	8.49	9.63	10.1	9.93	11.5	77	8.09	85	14.9	67
Est. % carbonates[b]	1.04	0.284	0.219	0.234	0.613	0.574	1.07	0.468	0.336	0.163	0.783	0.716	0.851	59	0.837	62	0.864	61

[a]%LOI (490°C): organic matter content (% dry sample weight) by loss on ignition at 490 °C
[b]Est. % carbonates: estimation of CO_3^{2-} content of the mineral fraction by subsequent ignition at 800°C (% dry sample weight exclusive of organic matter content).

Appendix 10

Crossvalidation: Prior and posterior classification and membership probabilities (continued overleaf). Single digit designations refer to *soil type* (1, 2, 3 & 4). The bolded entries indicate samples reclassified.

Observation	Prior	Posterior	1	2	3	4
1.3 sub	1	1	1.000	0.000	0.000	0.000
1.4 sub (mean)	1	1	1.000	0.000	0.000	0.000
1.7 sub (mean)	1	1	1.000	0.000	0.000	0.000
1.8 sub	1	1	1.000	0.000	0.000	0.000
1.10 sub	1	1	1.000	0.000	0.000	0.000
1.11 sub (mean)	1	1	1.000	0.000	0.000	0.000
1.13 sub	1	1	1.000	0.000	0.000	0.000
1.14 sub	1	1	1.000	0.000	0.000	0.000
1.3 top	1	1	1.000	0.000	0.000	0.000
1.4 top	1	1	0.799	0.000	0.187	0.014
1.7 top	1	1	1.000	0.000	0.000	0.000
1.8 top	1	1	1.000	0.000	0.000	0.000
1.9 top	1	1	1.000	0.000	0.000	0.000
1.10 top	1	1	1.000	0.000	0.000	0.000
1.11 top (mean)	1	1	0.997	0.000	0.000	0.002
1.13 top	1	**4**	0.002	0.000	0.179	0.819
2.2 sub	2	2	0.000	1.000	0.000	0.000
2.3 sub	2	2	0.000	1.000	0.000	0.000
2.4 sub	2	2	0.000	1.000	0.000	0.000
2.5 sub (mean)	2	2	0.000	1.000	0.000	0.000
2.6 sub	2	2	0.000	1.000	0.000	0.000
2.7 sub	2	2	0.000	1.000	0.000	0.000
2.9 sub	2	2	0.000	1.000	0.000	0.000
2.10 sub	2	2	0.000	1.000	0.000	0.000
2.11 sub (mean)	2	2	0.000	1.000	0.000	0.000
2.1 top (mean)	2	**4**	0.000	0.043	0.166	0.791
2.2 top	2	2	0.000	1.000	0.000	0.000
2.4 top	2	2	0.000	0.866	0.126	0.008
2.5 top (mean)	2	2	0.000	1.000	0.000	0.000
2.6 top	2	2	0.000	1.000	0.000	0.000
2.7 top	2	2	0.000	1.000	0.000	0.000
2.9 top	2	2	0.000	0.970	0.028	0.002
2.10 top	2	2	0.000	1.000	0.000	0.000
2.11 top	2	2	0.000	1.000	0.000	0.000
3.4 sub	3	3	0.000	0.000	0.973	0.027
3.6 sub	3	3	0.000	0.000	1.000	0.000
3.7 sub	3	3	0.000	0.000	0.995	0.005
3.8 sub	3	**4**	0.000	0.000	0.414	0.586
3.9 sub (mean)	3	3	0.000	0.000	0.999	0.001

Crossvalidation (continued): Prior and posterior classification and membership probabilities (continued overleaf). Single digit designations refer to *soil type* (1, 2, 3 & 4). The bolded entries indicate samples reclassified.

Observation	Prior	Posterior	S1	S2	S3	S4
3.11 sub	3	3	0.000	0.000	0.999	0.001
3.13 sub	3	3	0.000	0.000	0.585	0.415
3.14 sub	3	3	0.003	0.003	0.977	0.018
3.15 sub	3	**4**	0.000	0.000	0.278	0.722
3.16 sub	3	3	0.000	0.000	0.998	0.002
3.17 sub	3	3	0.000	0.000	0.999	0.001
3.18 sub	3	3	0.000	0.000	0.905	0.095
3.19 sub	3	3	0.000	0.000	0.733	0.267
3.20 sub	3	3	0.000	0.000	0.504	0.496
3.21 sub	3	3	0.000	0.003	0.988	0.009
3.22 sub (mean)	3	3	0.000	0.000	0.597	0.403
3.23 sub	3	3	0.000	0.000	0.966	0.034
3.26 sub	3	3	0.000	0.000	0.991	0.009
3.4 top	3	3	0.000	0.000	0.982	0.018
3.6 top	3	3	0.000	0.000	0.938	0.062
3.7 top	3	3	0.000	0.000	0.554	0.446
3.8 top	3	3	0.000	0.000	0.821	0.179
3.10 top	3	**4**	0.000	0.000	0.384	0.616
3.11 top	3	3	0.000	0.000	0.873	0.127
3.12 top (mean)	3	3	0.000	0.000	0.793	0.207
3.13 top	3	3	0.000	0.000	0.957	0.043
3.14 top	3	3	0.000	0.000	0.743	0.257
3.15 top (mean)	3	3	0.000	0.000	0.614	0.386
3.16 top	3	3	0.000	0.000	0.983	0.017
3.17 top	3	3	0.000	0.000	0.974	0.026
3.18 top	3	3	0.000	0.000	0.885	0.115
3.19 top	3	3	0.000	0.000	0.531	0.469
3.20 top	3	3	0.000	0.000	0.647	0.353
3.21 top	3	**4**	0.000	0.000	0.345	0.655
3.22 top	3	3	0.000	0.000	0.569	0.431
3.23 top	3	**4**	0.000	0.000	0.020	0.980
4.3 sub	4	4	0.000	0.000	0.003	0.997
4.5 sub	4	4	0.000	0.000	0.002	0.998
4.6 sub	4	4	0.000	0.000	0.113	0.887
4.7 sub	4	4	0.000	0.000	0.186	0.814
4.8 sub (mean)	4	4	0.000	0.000	0.306	0.694
4.9 sub	4	**3**	0.000	0.000	0.661	0.339
4.11 sub	4	4	0.000	0.000	0.123	0.877
4.12 sub	4	**1**	1.000	0.000	0.000	0.000
4.13 sub	4	**2**	0.000	0.862	0.008	0.130
4.14 sub	4	4	0.000	0.000	0.279	0.721

Crossvalidation (continued): Prior and posterior classification and membership probabilities.). Single digit designations refer to *soil type* (1, 2, 3 & 4). The bolded entries indicate samples reclassified.

Observation	Prior	Posterior	S1	S2	S3	S4
4.15 sub	4	4	0.000	0.000	0.132	0.868
4.16 sub	4	4	0.000	0.000	0.126	0.874
4.18 sub	4	4	0.000	0.000	0.021	0.979
4.19 sub	4	4	0.000	0.000	0.005	0.995
4.3 top	4	4	0.000	0.000	0.000	1.000
4.6 top	4	4	0.000	0.000	0.026	0.974
4.7 top	4	4	0.000	0.000	0.025	0.975
4.8 top	4	**3**	0.000	0.000	0.872	0.128
4.9 top (mean)	4	**3**	0.000	0.000	0.953	0.047
4.11 top	4	4	0.000	0.000	0.070	0.930
4.12 top	4	4	0.000	0.000	0.243	0.757
4.13 top (mean)	4	**2**	0.000	0.834	0.022	0.144
4.14 top	4	4	0.000	0.000	0.485	0.515
4.15 top	4	4	0.000	0.000	0.124	0.876
4.16 top	4	**3**	0.000	0.000	0.950	0.050
4.18 top	4	4	0.000	0.000	0.019	0.981
4.19 top	4	4	0.000	0.000	0.047	0.953